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Subject:

The Optimization of Photovoltaic Energy Production Through the Research and Development of a Configurable Solar Tracking System: A Case Study of Ouagadougou, Burkina Faso

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DEDICATION

I dedicate this work to Almighty God, whose grace, wisdom, and strength have guided me throughout this academic journey.

I dedicate this Master Thesis to my dear parents who, without their support and advice, I would not be at this level today.

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ABSTRACT

Access to clean and efficient energy remains a major challenge in many developing countries. This study presents the design, implementation, and testing of a configurable solar tracking system aimed at optimizing photovoltaic (PV) energy production in Ouagadougou, Burkina Faso. The system operates in both single-axis and dual-axis modes and was constructed using an Arduino Nano microcontroller, light-dependent resistors (LDRs), relays, and electrical linear actuators for solar panel movement. Two identical PV setups a fixed-tilt system and a dual-axis tracking system were installed side-by-side and monitored under the same environmental conditions. Custom data loggers recorded real-time voltage and current every minute during a full day of operation. Results showed that the dual-axis tracking system produced 21.85% more energy than the fixed system. These findings highlight the effectiveness of locally built, actuator-driven solar trackers in enhancing solar energy capture in Sahelian climates.

Keywords: Configurable Solar Tracker (CST); solar tracker; photovoltaic module; Environment; optimization; Internet of Things.

RESUME

L'accès à une énergie propre et efficace reste un défi majeur dans de nombreux pays en développement. Cette étude présente la conception, la mise en œuvre et les tests d'un système de suivi solaire configurable visant à optimiser la production d'énergie photovoltaïque (PV) à Ouagadougou, Burkina Faso. Le système fonctionne en modes à un axe et à deux axes, et a été construit à l'aide d'un microcontrôleur Arduino Nano, de résistances dépendantes de la lumière (LDR), de relais et d'actionneurs linéaires électriques pour le déplacement des panneaux solaires. Deux installations photovoltaïques identiques. Une à inclinaison fixe et une équipée d'un suiveur solaire à deux axes, ont été installées côte à côte et surveillées dans les mêmes conditions environnementales. Des enregistreurs de données personnalisés ont mesuré en temps réel la tension et le courant chaque minute pendant toute une journée d'exploitation. Les résultats ont montré que le système à deux axes a produit 21,85 % d'énergie de plus que le système fixe. Ces résultats mettent en évidence l'efficacité des suiveurs solaires locaux, motorisés par actionneurs, dans l'amélioration de la capture de l'énergie solaire dans les climats sahéliens.

Mots-clés : Suiveur Solaire Configurable (SSC) ; suiveur solaire ; module photovoltaïque ; l'Environnement (TRE) ; l'optimisation, Internet des Objets.

ACRONYMS AND ABBREVIATIONS

ACS712:	Current Sensor Module (based on Hall Effect)
AI:	Artificial Intelligence
ANFIS:	Adaptive Neuro-Fuzzy Inference System
ARDUINO IDE:	Arduino Integrated Development Environment
ATMEGA328P:	Microcontroller used in Arduino boards
CST:	Configurable Solar Tracker
ESTs:	Environmentally Sound Technologies
GIS:	Geographic Information Systems
IDE:	Integrated Development Environment
IoT:	Internet of Things
LDR:	Light Dependent Resistor
LCD:	Liquid Crystal Display
MPPT:	Maximum Power Point Tracking
PCB:	Printed Circuit Board
PID:	Proportional-Integral-Derivative (Control Algorithm)
PV:	Photovoltaic
RTC:	Real Time Clock
SAM:	System Advisor Model
SD:	Secure Digital (Memory Card)
SDGs:	Sustainable Development Goals
UN:	United Nations
UNEP:	United Nations Environment Program
WTO:	World Trade Organization

List of Symbols

Symbol	Meaning
P:	Power (in Watts)
I:	Current (in Amperes), measured using the ACS712 current sensor
V:	Voltage (in Volts), measured using the DCVS30-H16S8 voltage sensor
E:	Energy (in Watt-hours), cumulative energy output
Δt:	Time interval – used in power and energy calculations
Et:	Energy produced by the solar tracker system
Ef:	Energy produced by the fixed PV system
η:	Gain, implied in energy optimization comparisons
R:	Resistance, used implicitly when describing electrical modeling
T:	Temperature – referenced when considering environmental impact on PV
θ	used for angles (sun orientation or panel tilt)

LIST OF FIGURES

INTRODUCTION

I. Context and Justification

Climate change is a long-term change in weather patterns from the tropics to the poles, causing global threats to sectors like agriculture, health, biodiversity, and tourism, energy, and requiring global efforts and policies to address its impacts and ensure sustainability[1].

Thus, climate change is a big issue in the world. It is mostly caused by people. Burning fuel makes about 9.5 billion tons of CO_2-equivalent emissions each year. Cutting trees adds 1.5 billion tons more. The energy sector was responsible for about 73.2% of the total 49.4 billion tons of CO_2-equivalent emissions in 2016. This shows we must act quickly, highlighting the urgent need for sustainable energy solutions[2].

One of the most significant research contributions to the understanding of SDG 7 has been a study on energy poverty in developing countries, which highlights the role of human capital in addressing energy access. The study utilizes a sample of 108 developing economies and employs the Pedroni cointegration technique to confirm long-run relationships among the variables.[3]. For instance, Nigeria faces significant challenges in balancing energy needs and climate commitments, with climate change leading to severe impacts. The study highlights the potential of renewable energy sources, particularly solar energy, to reduce emissions and support sustainable development, while also addressing necessary safety measures for solar energy applications[4]. Previous studies indicate that solar energy is one of the most effective sources of energy with the potential for reducing greenhouse gas emissions. Likewise, this study shows that solar energy through PV systems can satisfy demand and protect the environment.[5]

To make up to the energy shortfall, the development of alternative and renewable energies is essential. Among these alternative and renewable energies, solar energy is of the utmost importance as it is considered to be green energy and, above all, inexhaustible on a human scale. Burkina Faso has a high solar energy potential. The country receives about 5.5 kWh/m² of sunlight per day. It has 3,000 to 3,500 hours of sunshine per year, with around 8.3 hours of sunlight each day[6]. Indeed, Burkina Faso has prioritized solar energy solutions to address these challenges. Small scale utility solar farms and off grid solar systems are being established to generate electricity for the rural population. This will allow the country to reduce imports of fossil fuels and contribute to the fight against climate change by minimizing carbon dioxide emissions.

The country has abundant sun to ensure that it utilizes the energy to address one part of the growing demand of its population. Small-scale utility solar farms and off-grid solar systems are being developed to generate electricity for rural populations. One such initiative is underway in Digré, located in the Central-Eastern region approximately 107 km from Ouagadougou, as illustrated in Figure 1.

Figure 1: PV off grid in Digré

Sahel area which has high potential in receiving solar energy as experienced high amount of sunlight has un-matched chances of solar energy utilization. Nevertheless, the region also has problems such as energy deficits, particularly in the rural area, and the search continuous for environmentally friendly ways of decreasing dependence on imported hydrocarbons. For the aforementioned challenges, effective solutions require new main ideas to enhance the effectiveness of solar energy systems.

One promising approach to the problems is the use of sun tracking systems which improve the efficiency of PV panels based on their ability to track the position of the sun during the day. This technology has the possibility of boosting energy production and more especially in regions that receive high solar intensity such as Burkina Faso.

In areas where energy availability and utilization are critical, integrating applications of solar tracking systems with solid PV networks could revolutionize energy delivery and conservation. In addition to catering to local power needs, this strategy does help meet global specious of combating climate change proactively and the encouraging of renewable resources usage.

II. Problem statement

Burkina Faso, a developing country that has a huge need for energy to develop its economy and meet the energy comfort requirements of its mostly young and growing population. Fossil fuels provide most of the energy used in the country[7]. The principles considered for the optimization of a solar tracking system include the need to overcome challenges such as partial shading conditions (PSCs), which cause non-linear and multi-peak power output. To achieve optimization, different maximum power point tracking (MPPT) techniques are employed, each based on specific control and optimization principles. These principles help improve the system's ability to adjust and track the maximum power output efficiently, especially under PSCs[8].

An Adaptive Neuro-Fuzzy Inference System (ANFIS) helps improve how the solar tracker follows the sun[9]. The system is controlled by a PID controller optimized with AI techniques such as Particle Swarm Optimization and Bat Algorithm. Experimental results revealed superior performance in settling time and overshoot, emphasizing the role of advanced optimization in improving solar tracking[10]. In the context of improving solar energy efficiency, another research has analyzed the solar resource potential in Nigeria across various tracking surfaces. The use of models such as Perez anisotropic and Koronakis isotropic, solar radiation was estimated on inclined, single-axis, and dual-axis tracking systems in nine locations. Results showed that dual-axis trackers achieved the highest energy gain which has annual increases ranging from 1.86% to 31.52% depending on the region and tracking configuration. This information is critical for guiding the design and installation of efficient solar tracking systems to enhance energy generation and address electricity shortages[11]. Therefore, our study aims to optimize PV energy production and experimentally compare the energy performance of fixed, single-axis, and dual-axis solar tracking systems in Ouagadougou. We implemented an energy monitoring system to log real-time solar data, overcoming one major limitation of previous studies: the predominant use of fixed solar panels and the lack of detailed energy data logging in similar local conditions.

III. Research questions, hypotheses, and objectives

III.1 Research Questions

To well guide this applied research, the main research question is formulated as follow:

Can photovoltaic energy production in Ouagadougou be efficiently optimized by the development of a configurable solar tracking system and two data loggers?

The specific research questions are:

- i What solar tracking technologies exist, and can they work well in Ouagadougou?
- ii How can a solar tracker and two data loggers be Deployed to get more solar energy?
- iii How can the energy from the solar tracker be compared to the fixed PV system in real conditions?

III.2 Research Hypothesises

The main research hypothesis is:

The development of a configurable solar tracking system and two data loggers can contribute to efficiently optimize photovoltaic energy production in Ouagadougou.

The specific research hypotheses are:

- i Solar tracking systems deployed in secure locations improve PV panel energy efficiency compared to fixed systems under the environmental conditions of Ouagadougou.
- ii Existing solar tracking technologies are identifiable and are adaptable for use in the Sahelian context, particularly in Ouagadougou.
- iii solar tracking system, when properly designed and integrated with a data logger, enhances the control and efficiency of photovoltaic energy production.

III.3 Research Objective

To accomplish this applied research, the main research objective is settled as follow:

To develop a configurable solar tracking system and two data loggers for efficiently optimizing photovoltaic energy production in Ouagadougou.

The specific research objectives are:

- i To evaluate existing solar trackers for Ouagadougou’s sun and weather.
- ii To make a configurable solar tracker (single or dual axis) and two data loggers.

iii To compare energy from the tracking system and the fixed panel under the same conditions.

CHAPTER 1: LITERATURE REVIEW

This chapter presents an overview of the methods and technologies relevant to the research. Different techniques for optimizing solar panel placement are presented in both urban and rural settings. Therefore, a review of solar radiation assessment methods is presented, including a brief history, their relationship to sustainable energy development, and the description of tools and algorithms.

1.1 Energy consumptions in cities

The world over, cities are racing to transform how they use energy through better urban planning, smarter buildings, and waste reduction-both because they are the source of most of our carbon emissions and their populations are growing [48]. For instance, India is an emitter due to its high energy consumption materials and fossil fuels and stands third among emitters. Urban energy infrastructure has to be revamped and renewable solution promotion has to be boosted for climate goals [49]. By 2050, it is predicted that energy consumption prediction using machine learning will significantly enhance sustainable energy management as efficient algorithms become integral in accurately forecasting energy needs, optimizing resource allocation, and reducing environmental impacts across urban areas experiencing rapid growth [50]. For instance, In the municipality of Loures (a city of approximately 201,590 inhabitants) located in Portugal. The spatial analysis has revealed significant variations in energy consumption based on urban morphology and density. High-density urban areas exhibit the highest energy demand, while rural zones consume significantly less due to lower population concentration and building characteristics. It is observed that integrating Geographic Information Systems (GIS) allows policymakers to identify energy-intensive zones and implement targeted strategies for efficiency improvements and renewable energy deployment[12]. Indeed, cities use a lot of energy, and this can cause more carbon emissions. A study in China (2012–2022) shows that the digital economy helps to reduce these emissions. But more people, more buildings, and more factories make emissions go up. Good use of energy and better technology help bring them down. The study says that cities should use these ideas to make cleaner and smarter plans[13]. Moreover, the energy consumption is rising due to population growth and poor building insulation in Ouagadougou. Public buildings alone use about 30 GWh per year, mostly for cooling. This shows the need for better energy planning and the use of renewable energy in Sahelian cities[14].

1.2 Energy production optimization

Many cities around the world are facing the increase of energy challenges in the future due to population growth combined with urbanization and the rising demand for electricity driven by technological advancements. The urban areas are at the center of this trend. Globally, all sectors (agricultural, industrial, residential, commercial, etc.) contribute significantly to the growing exploitation of energy resources[15], with cities and urban areas being places where energy consumption is highly concentrated and often inefficient. For instance, in Nigeria, in Lagos (the most populous city of the country and commercial capital), energy demand from the transport sector is rising sharply, with projections showing If the average vehicle age is not lowered from 40 to 22 years, and the rate of vehicle increase is not slowed from 5% to 2%, the city could fail to meet its 2032 goal of cutting emissions by 2032[16].In England, the analysis of 346 Local Authority Units shows that overall energy consumption scales sub-linearly with population size, regardless of the urban or rural classification[17].

1.3 Solar Tracking System

1.3.1 Background on a solar tracker

A solar tracking system is a device that turns the solar panels toward the sun during the day. It helps the panels stay in the best position to catch sunlight. The system used sensors and a small computer (called a microcontroller) to do this job automatically[18]. The comparison between fixed and tracking PV systems shows that fixed-mount systems in Jakarta produce around 1379 kWh/kWp per year, while tracking systems produce about 1672 kWh/kWp annually. The tracking system, which keeps the solar modules at an optimal angle to receive direct sunlight, results in higher energy output than the fixed-mount system[19]. Thanks to solar tracking systems, especially dynamic single-axis trackers, energy yield improves significantly by adjusting panel angles to follow the sun, resulting in a 35% increase in monthly electricity production compared to fixed systems. The dynamic tracker's ability to optimize performance in both sunny and cloudy conditions enhances solar energy capture, with a 50% increase in production on cloudy days. The dynamic tracker produced 1305 kWh/kWps, outperforming the fixed system's 915 kWh/kWp over time. Overall, solar tracking improves energy yield efficiency, maximizing energy generation and optimizing land use[20]. A solar tracker system is shown in the figure 2.

Figure 2: Example of a solar tracker [21]

In static solutions, where solar panels remain in a fixed position, the full potential of solar cells is not used. To increase even more the energy output of the single solar panel unit, a solar tracker is filling up this gap. As the sun wanders from east to west during the day, adding a mechanism with a turret head would convert the incident east to west solar radiation into electric energy. It exists as well another single-axis tracking solution, which swivels horizontally around a vertical axis. For this raison, the previous type of single-axis trackers is not widely used. In single-axis vertical solar trackers, it is also necessary to face the surface of the panels at the most optimal tilt. This tilt varies depending on the different latitudes. For example, in Stavanger (Norway), the most optimal tilt angle would be 40°. But in more down south place like Aveiro (Portugal), it would be around 35°[22]. Finally, an experiment at Joseph KI-ZERBO University showed that a dual-axis solar tracker collected up to 52.33% more solar radiation than a fixed panel tilted at the local latitude in Ouagadougou. The tracker recorded 800–1000 W/m² of radiation for about 8 hours on a clear day[23].

1.3.1.1 Based on Tracking Mechanism:

The Tracking mechanisms can be categorized into several types, each with its unique method of operation:

a. Passive Trackers

Passive trackers employ the thermal expansion of liquids or gases to adjust the solar panel's position without the use of electricity. They are simple and low-cost but lack precision, which can result in less effective solar energy capture[24].

b. Active Trackers

Active trackers use motors and sensors to dynamically adjust the orientation of the solar panels. They are more accurate and efficient in following the sun's path but require an external power source to operate the motors and sensors, which increases energy consumption[25].

c. Sensor-Based Trackers

Sensor-based trackers rely on light sensors (such as photodiodes or (light dependent resistor) LDRs) to detect sunlight intensity and adjust the panel angle accordingly. This real-time response mechanism allows for optimal energy absorption but depends on the effective operation of the sensors[26].

d. Time-Based Trackers

Time-based trackers utilize pre-programmed algorithms to predict the sun's position based on the time of day and geographic location. They do not need sensors but may require occasional recalibration to remain accurate, especially during seasonal changes.

e. Hybrid Trackers

Hybrid trackers combine the features of sensor-based and time-based systems to achieve enhanced accuracy and efficiency. This approach allows them to respond to immediate lighting conditions while relying on predictive algorithms, resulting in more effective solar energy capture overall[27].

1.3.2 Solar photovoltaic panel

A solar panel (called PV panel) converts sunlight into electricity. It has many small parts called solar cells. These cells are put together to make one big panel. When sunlight hits the panel, the solar cells make electricity. More sunlight gives more power. But when there is shade or clouds, the power becomes less. To help the panel give more energy, we use a controller and another part called a boost converter. These help the panel work better. There are different ways to connect the solar cells. Some ways help stop power loss when part of the panel is not in the sun. Solar panel technology keeps improving. This helps people use more clean energy from the sun.[28].

The power of a solar panel depends on sunlight and temperature. The panel produces more electricity When there is more sunlight. But when it gets too hot, the panel works less well. This is because too much heat makes it harder for the solar cells to produce energy. Studies showed that when the temperature goes up, the solar panels can lose between 2.9% and 9.0% of their power. This depends on the type of panel and the weather. Moreover, the panel's temperature can change many times during the day. This also changes how much energy the panel gives. It is good to let the panel stay cool to stop this problem. We can do this by adding air flow or using other cooling methods. This helps the panel give more energy and last longer.[29].

1.4 Electrical and Mechanical details of a Solar Tracker

1.4.1 Mechanics of a solar tracker

Fundamentally, the mechanism relies on motion mechanisms in solar tracking systems which is categorized into rotation mechanisms and motion transmission systems. A single-axis system moves solar panels follow the sun in one direction, either side to side (azimuth) or up and down (tilt). A dual-axis system combines both directions that helps the panels to follow the sun more fully during the entire day and across seasons. For motion transmission and gear-driven systems utilize components like gear reducers, rack pinion setups and worm gears to adjust panel positions. Moreover, linear actuators that are whether hydraulic or electric move the panels linearly, and belt and pulley systems provide smooth motion, enhancing the overall performance and efficiency of solar tracking systems.[30].

It is important to understand the mechanical parts. The improvement of how the system works and how long it lasts in solar tracking systems. The design of these systems includes a variety of carefully selected components. Each component contributes to the overall efficiency of the tracking mechanism. The following sections will explore the mechanical elements that play a pivotal role.

A. Linear Actuators

The solar tracker has a top part called the head, where the solar panels are fixed. This head is placed on joints so it can turn in two directions: left and right (x-axis), and up and down (y-axis). To make the head move, we use a tool called a linear actuator. This device changes electrical energy into straight movement. In this project, we used an electric linear actuator. It helps move a metal rod (piston) forward and backward to push or pull. A 12V DC motor turns fast, but a gearbox slows it down. Then, it turns a screw that makes the rod longer or shorter. The length of the movement depends on the design and can be from 500 mm to 1000 mm.[31].The example of electrical linear actuator as showing in figure 3

Figure 3: Example of electric linear actuator appearance [31]

B. Worm gear transmission

A slewing drive is a gearbox, which transmits torque to rotation and holds the radial and axial loads of the whole structure. A DC motor converts the electric energy into the mechanical movement of a worm shaft. Then via a worm gear transmission, mechanical energy rotates the solar tracker's head. Below is placed a picture in figure 4 of a worm gear system.[32].

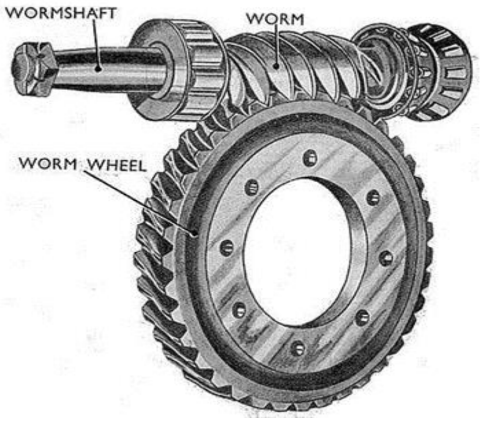


Figure 4: Worm gear transmission [32]

1.4.2 Electrics of a solar tracker

Electrical motors can be controlled by a programmable logic controller (PLC) or another microcontroller. A steering controller programmed in one of the sun-tracking techniques opens a DC or an AC circuit for the engines and thereby adjusts the head of a solar tracker towards the incident radiation.

Solar panels produce the direct current. After the photons are turned into electric energy, the current flows to the electric box. The electric current needs to pass first a circuit breaker and then arrive in the power inverter, where the direct current is inverted to the 230 V, 50 Hz alternating current. Using two 12 V DC motors for the solar tracking system, the 230 V AC must be transformed into a constant 12 V DC. Therefore, a transformer needs to be used. Sometimes, when the sun falls on the back of solar panels, the tracking system doesn't have enough energy to rotate the head towards the radiation. In this case, it is recommended to use a battery. Therefore, the motors and the controllers would receive a steady current[33].

1.5 Environmentally Sound Technologies (ESTs)

As already said in the introduction part, the definition of Environmentally Sound Technologies (ESTs) is based on Agenda 21, which arose from the United Nations Conference on Environment and Development [34], otherwise known as the Earth Summit, held in 1992 [35].

However, ESTs are not just individual technologies. They can also be described as complete systems that include know-how, procedures, goods and services, and equipment, as well as organizational and managerial procedures for promoting environmental sustainability.

1.5.1 A short history on ESTs

Environmentally Sound Technologies (ESTs) encompass innovative solutions that reduce environmental harm, including low-waste and zero-waste technologies[36]. In addition, the definition of Environmentally Sound Technologies (ESTs) aligns with the principles set forth in Agenda 21, which emphasizes sustainable development and environmentally responsible innovation[37], which arose from the United Nations Conference on Environment and Development (UNCED), otherwise known as the Earth Summit, held in 1992 (Halls, 2015). However, ESTs are not just individual technologies. They can also be defined as total systems that include know-how, procedures, goods and services, and equipment, as well as organizational and managerial procedures for promoting environmental sustainability.

Technology Transfer (TT) is essential for smart city development and climate change mitigation. The UNFCCC supports EST transfer through global collaboration, ensuring technology exchange between developed and developing nations. In Bahrain, green technology adoption requires strategic policies, effective transfer models, and innovation across the technology cycle. Addressing barriers to technology transfer is key to enhancing smart city performance and sustainability[38].

For several decades ago, little progress has been made in the trade of ESTs without the participation of developing countries. However, since 2006, with the participation of developing countries, trade in ESTs is making significant progress, but it’s still dominated by developed countries and emerging economies. The figure below (**Figure 5**) shows the evolution of trade in ESTs from 2006 to 2016.

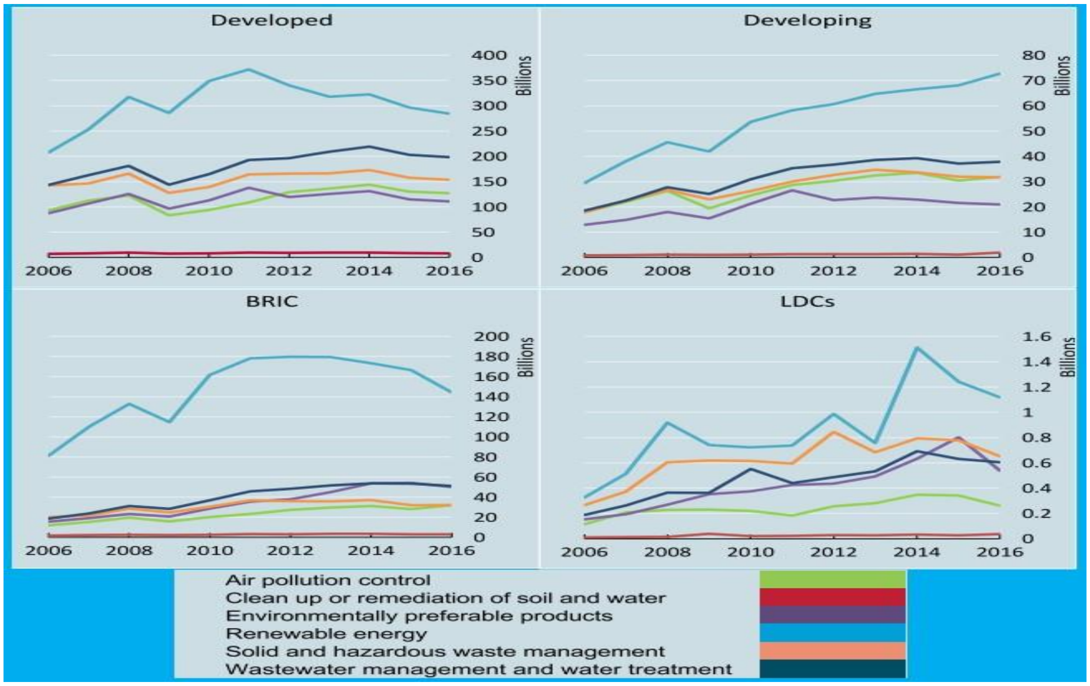


Figure 5: Trade in selected ESTs [39]

1.5.2 ESTs and Sustainable development

Sustainable development means using resources today in a way that does not damage the future. In 2015, the UN set 17 SDGs to improve the world by 2030. Mining supports these goals by creating jobs but also causes pollution and conflicts. Africa has rich minerals, yet some nations face poverty and poor management. Better rules and fairer resource use can make mining more beneficial.[40]. International trade plays a crucial role in disseminating environmentally sound technologies (ESTs), and its impact on domestic firms' green innovation especially for importers remains unclear. The imported ESTs can reduce local green innovation. However, factors like technological proximity, learning capacity, and government subsidies can help lessen this impact. Trade and patent data from 2000 to 2016 support these findings[39]. The transfer of environmentally sound technologies (ESTs) through trade, adoption, and use can support achieving specific Sustainable Development Goals (SDGs) among the 17 set by the United Nations (UN). For this, clear policies are necessary from governments, communities, and other stakeholders, who must collaborate to enable sustainable solutions. According to the document, BRICS countries play a key role in climate change mitigation through EST adoption, which contributes to reducing greenhouse gas emissions and achieving SDGs[41]. The world trade organization database is in the below figure 6.

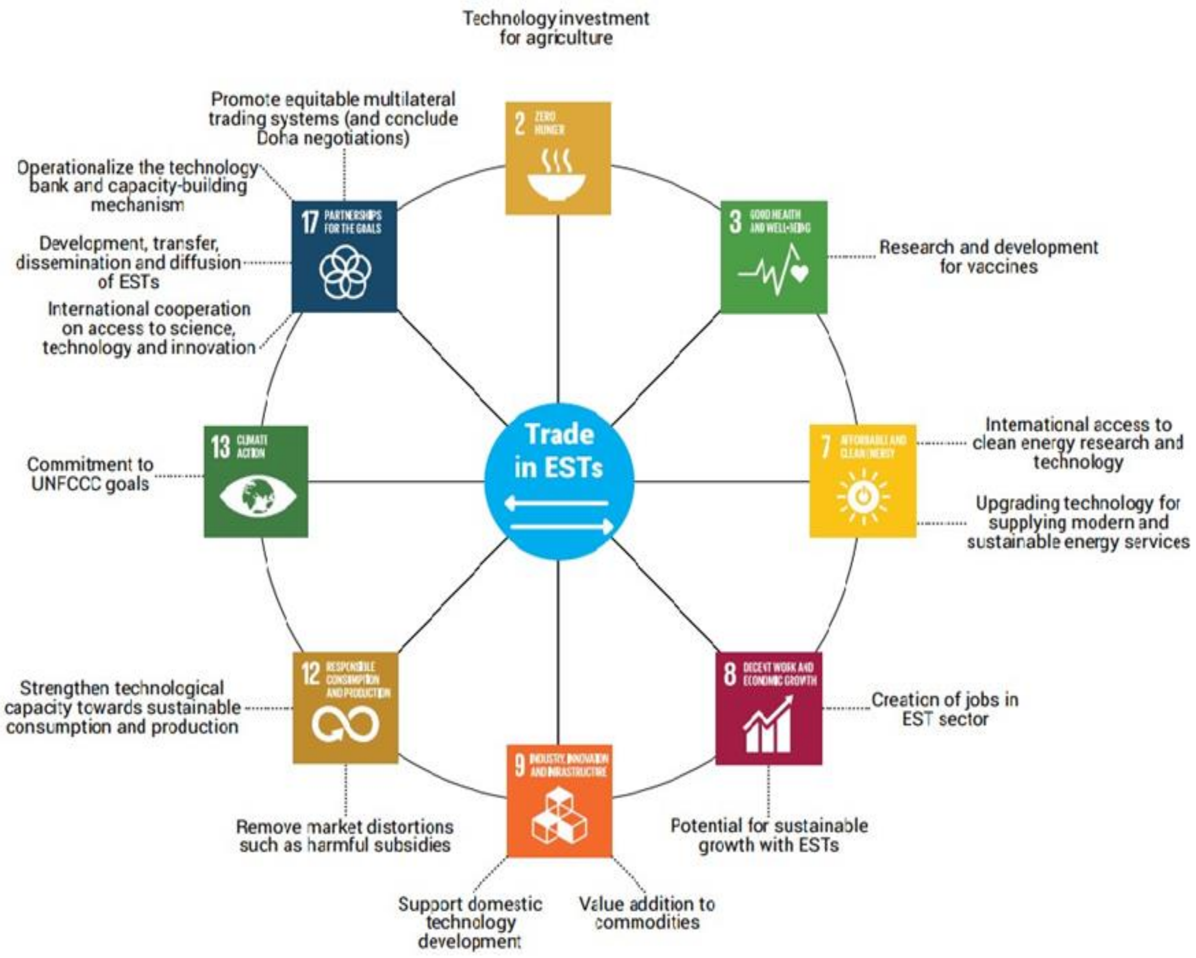


Figure *6:* World Trade Organization (WTO) database on trade in services, country- and company-level data, as well as scientific publications. [42]

1.5.3 Overview and Evolution of the Internet of Things

Everyday objects are interconnected through sensors and intelligent devices as part of the Internet of Things. These devices communicate through specific protocols that enable smooth data exchange. They work together within a system that supports distributed, intelligent computing. The system IoT can applied in fields like healthcare, transportation, and environmental monitoring. Understanding the different layers of the IoT stack and its technologies helps build solutions for real-world challenges[43]. Moreover, the convergence of physical and digital realms through the Internet of Things drives the development of Vehicular IoT (V-IoT), transforming urban transportation with affordable, compact sensors and actuators[44]. The following figure 7 is showing the evolution of IoT over years.

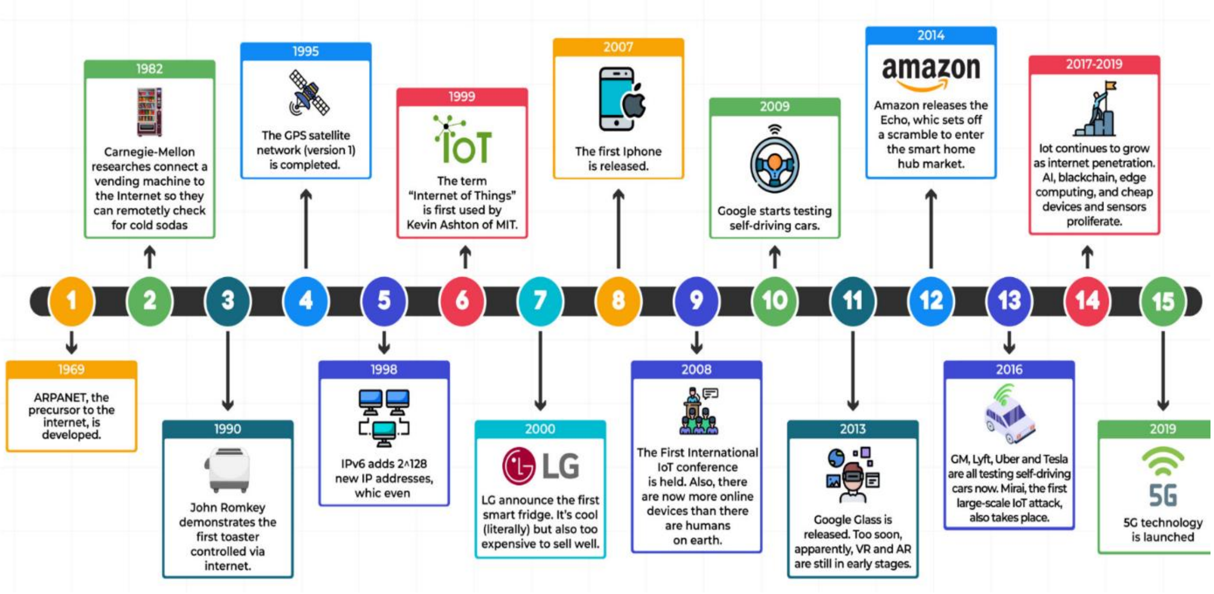


Figure 7: the evolution of the Internet of Things (IoT) over the years [45]

Finally, most people used energy without thinking about how it affects the Earth. But now, the Internet of Things (IoT) can help us change that. Thanks to IoT, companies can better control how they use energy. This reduces waste, saves money, and lowers CO_2 emissions, which is good for the planet. Another problem in the energy sector is that there is no strong planning system or good way to guess how much energy people will need in the future. IoT in Industrial and Manufacturing Applications. Factories are working differently now because of IoT. In the machine tool industry, it helps to make machines work by themselves through automation. IoT technologies enable machines to gather and share real-time data about their performance and environment, which enhances transparency and efficiency in production processes. This integration leads to significant benefits, such as optimized operations, improved product quality, reduced waste, and shorter production times. Moreover, IoT facilitates predictive maintenance, allowing manufacturers to foresee potential issues before they lead to downtime, ultimately extending the lifecycle of equipment [46]. The Internet of Things (IoT) also contributes significantly to cost reduction across various sectors. It enhances energy efficiency, optimizes maintenance processes, and integrates legacy systems. Moreover, by leveraging real-time data collection and analysis, IoT technologies enable organizations to minimize operational expenses and improve productivity. IoT-enabled manufacturing environments generate vast amounts of sensor data, presenting both challenges and opportunities for advanced process analytics. Comparisons of deep learning methods with simpler statistical approaches, such as Partial Least Squares, have been made for predicting key process variables like pump motor speed and water flow rate. These findings illustrate how leveraging IoT data can lead to optimized operations, reduced waste, and significant cost reductions in industrial applications[47].

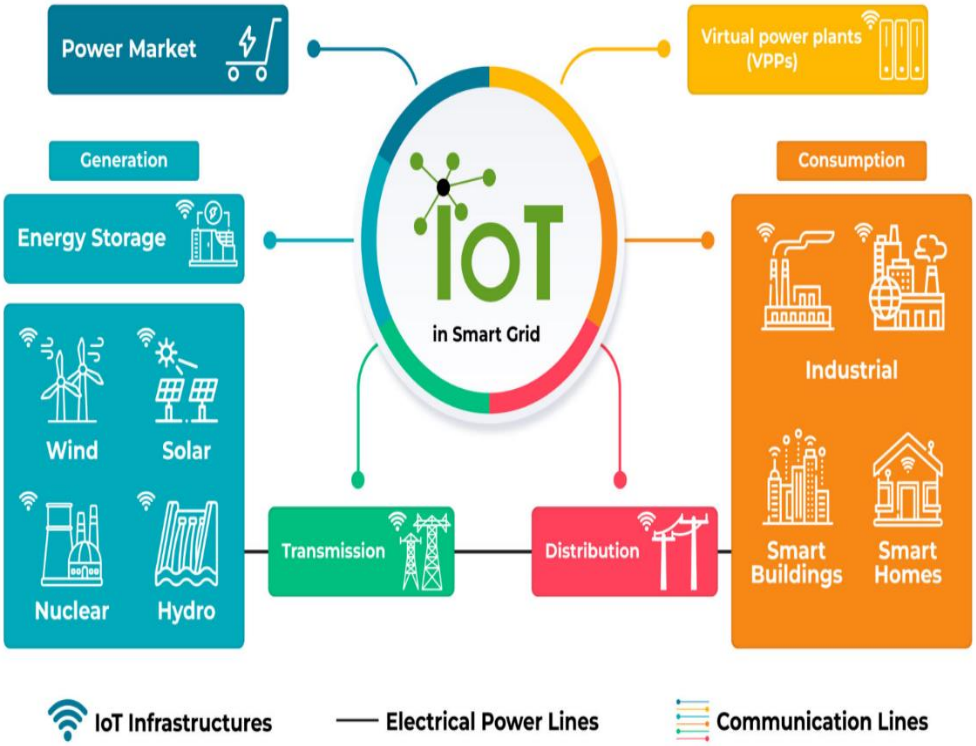


Figure 8: The entire IoT ecosystem of the Energy Sector

Source[45]

1.6 Performance Characteristics of PV Technologies

This section explores the performance characteristics of fixed, single-axis, and dual-axis photovoltaic (PV) systems to understand their energy efficiency, cost and operational advantages.

1.6.1 Fixed PV Module Performance

Accurate energy yield estimation is essential for predicting the performance of fixed photovoltaic (PV) modules. The most energy yield models depend on Typical Meteorological Year (TMY) data that have an hourly time resolution, which can reduce the accuracy of predictions by smoothing out short-term variations in solar irradiance. This averaging effect tends to underestimate high irradiance levels, which are critical for fixed PV systems, leading to an underestimation of inverter clipping losses and an overestimation of the performance ratio[48]. Despite certain modeling limitations, fixed photovoltaic (PV) systems have demonstrated high efficiency and cost-effectiveness in real-world applications. A study in Malaysia on off-grid telecommunication towers found that fixed PV systems combined with battery storage delivered the lowest energy cost and best performance. This success is largely attributed to the use of high-efficiency panels and MPPT controllers optimized for tropical climates. These findings confirm the viability of fixed PV systems as an affordable and sustainable energy solution[49].

1.6.2 Single-Axis Tracking PV Performance

In Taipei, solar panel systems with single-axis trackers, which follow the sun's movement, can produce significantly more energy than fixed systems. Long-term field tests showed an overall increase of 24.2% in energy generation from March 2010 to May 2012. On clear days, the energy gain reached up to 39%, and in high solar radiation areas, the expected increase can be as high as 37.5%. Although traditional tracking systems are often expensive and complex, a low-cost one-axis three-position (1A-3P) tracker was developed, offering 25–37% more energy with similar installation costs to regular rooftop systems. Even when not perfectly facing south, the energy loss was minimal, making these trackers a practical and efficient option for improving solar power output[50]. One of the outcomes is that mechanical and control systems of single-axis trackers significantly enhance the energy output of solar panels. The mechanical design allows these trackers to follow the sun's movement, resulting in a minimum increase of 19% in energy production, with some configurations reaching up to 47.84%. This boost in efficiency is further supported by experimental data and simulation Furthermore, control systems such as the single-axis tracker add to the energy generation by adjusting the horizontal positioning of the panel to follow the sun's path during the day. Tracking systems differ from sun fixed systems where the latter is fixed in position. By moving along the azimuth angle, tracking systems ensure maximum exposure to sunlight and therefore, maximum energy generation. The single-axis tracking system accomplished a great increase of energy, thereby becoming to give the solution that is cheap and effective for upgrading the entire system[51][52]. In one example from Baluchistan, Pakistan, results showed that larger solar power plants can produce cheaper energy. Using a computer tool called SAM, it was found that single-axis trackers, which move the solar panels to follow the sun, generate more energy at a lower cost than fixed systems. They are also less expensive than the more complex dual-axis systems. The cost of energy with single-axis systems was 1.79 USD per kilowatt-hour, compared to 2.14 USD for fixed systems. This suggests that single-axis systems are a smart and cost-effective option for providing solar power in areas without access to the main electricity grid[53].

1.6.3 Dual-Axis Tracking PV Module Performance

Solar tracking systems provide greater energy yields for photovoltaic solar panels by physically moving to follow the sun in its course through the sky. It moves in two directions: side to-side and up-and-down. This is how the panels gather sunlight throughout the day. On sunny days, these trackers can yield roughly a 53% increase in output above the fixed panels. Meanwhile, after considering the energy consumed in movement and operation, the net gain is approximately 49%. On cloudy days, they are hardly effective, offering no more than 2% additional energy. Hence, dual-axis trackers are remarkable under clear weather conditions, but of little use during cloudy weather[54]. Despite their superior energy yield, dual-axis solar trackers have some problems with maintenance and reliability. These systems move solar panels to follow the sun in two directions up and down, and side to side. This helps the panels get more sunlight and make more energy. But this movement needs more parts like motors, sensors (LDRs), and a microcontroller (ATMEGA328P with Arduino). Because they have many parts, they are harder to take care of than fixed panels. Dust, wind, and rain can make sensors and motors stop working [55][56]. Another critical aspect is the effect of the environment on dual-axis solar trackers. Dust, clouds, rain, and heat can reduce how well the system works. The tracker uses sensors and Arduino to follow the sun and collect more energy. A real-time monitoring system checks the panel's performance. The system gave 55.38% more energy than a single-axis tracker, but it needs regular care to stay effective[57].

Conclusion

This This literature review has helped to better understand how to optimize solar energy production through solar tracking systems, particularly in regions with strong sunlight such as Ouagadougou. Several studies show that fixed solar panels, although commonly used, have a major limitation: they do not follow the movement of the sun, which results in a significant loss of solar radiation throughout the day. In contrast, solar tracking systems, especially dual-axis trackers, allow panels to orient themselves in real time according to the sun's position, both horizontally (azimuth) and vertically (elevation). This leads to a considerable increase in energy output, achieving improvements of as much as 53% over fixed-panel systems.

The critical analysis highlights that, although single-axis trackers are more efficient than fixed panels, they remain less performant than dual-axis trackers, particularly in terms of orientation accuracy and the amount of energy captured. However, these systems require robust mechanical components (such as linear actuators) and an intelligent control system capable of ensuring continuous proper operation, especially in secured areas. Without reliability, the energy gain can be compromised. Given these observations, this research proposes to develop a configurable solar tracking system, capable of operating either in single-axis or dual-axis mode, depending on needs and available resources. This system would be paired with a data logger to monitor energy performance in real time. This locally developed and adaptable technological solution would effectively address the energy challenges of the Sahel, while ensuring better efficiency and system resilience.

CHAPTER2: MATERIAL AND METHOD

Introduction

In the pursuit of optimizing photovoltaic energy production in regions with high solar potential, it becomes crucial to design systems that are both technically effective and adapted to local environmental conditions. Chapter 2 presents the material and methodological approach undertaken in this research, with a focus on the implementation and evaluation of a configurable solar tracking system in Ouagadougou, Burkina Faso—a city characterized by intense solar irradiation and numerous high-security zones that demand stable, localized energy solutions. This chapter outlines the geographical context of the study area, details the experimental design and data collection procedures, and describes the tools, electronic components, and software environments used to build and test the proposed system. Through a comparative framework between fixed and tracking photovoltaic systems, this methodological approach aims to generate reliable, real-world data that can guide the optimization of solar energy systems in Sahelian urban settings.

2.1 Study area

Burkina Faso benefits from abundant solar energy resources, making it an ideal location for solar energy projects. Ouagadougou, the capital city that has been chosen as the study area for this work. It hosts more high-security areas than other cities in the country, including government buildings, embassies, military zones and key infrastructure. This makes it a suitable place to test solar tracking systems to improve energy production in sensitive zones. Burkina Faso is a landlocked country in West Africa, bordered by Mali to the north and west, Niger to the east, Benin to the southeast, and Ghana, Togo, and Côte d'Ivoire to the south. Covering an area of around 274,000 km², Ouagadougou is located in the central part of the country and experiences a tropical climate. The city experiences three main seasons: a cool and dry season from November to February, a hot season from March to May, and a rainy season from June to October. The Sahel gets a lot of sun but has little rain. It has short rainy seasons and long dry periods. This makes it good for solar energy, but also brings problems like droughts and not enough water. Because many people live there, it is important to study how the climate affects water, food, and life in the area. [58]. The figure 9 below is the map of Ouagadougou

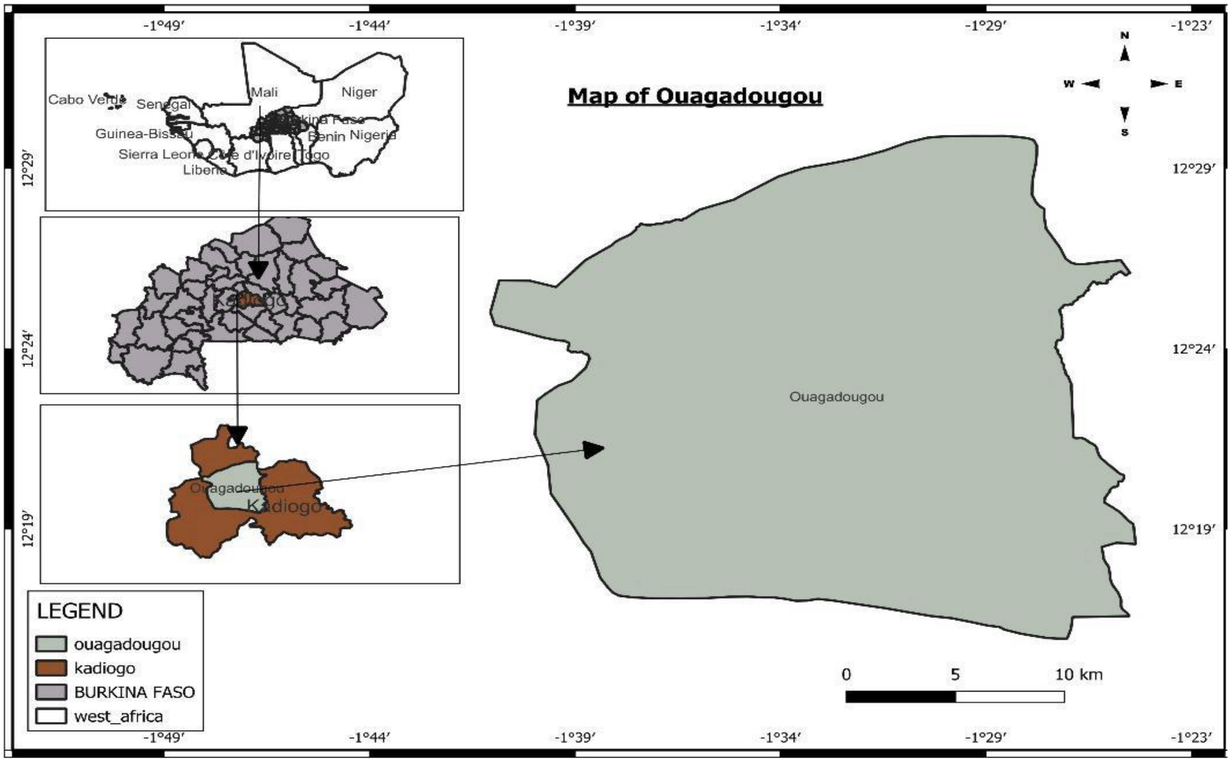


Figure 9: Study Area

2.2 Data Collection

Two on-site experimental setups were carried out to obtain the data needed to reach the different objectives of this study: the first one consisted of a photovoltaic system equipped with a configurable solar tracking system (single or dual axis), and the second one consisted of a traditional fixed-tilt photovoltaic system.

The following configurations and materials were used for the two systems:

1. The two systems were installed at Joseph Ki-Zerbo University in Ouagadougou.
2. The solar tracking system was designed to be configurable and allowed to switch between single-axis and dual-axis tracking modes depending on the study requirements.
3. Each system (tracker and fixed) was connected to its own data logger, and both data loggers were built using identical electronic components and placed in similar enclosures to ensure uniformity and fairness in the experimentation.
4. A DC voltage sensor (DCVS30-H16S8) was used to measure voltage in each system.
5. A current sensor (ACS712) was installed in each system to record current output.
6. A rheostat was added to each circuit to form a resistive load that allowed current to flow and be measured.
7. From sunrise to dusk, each data logger was set up to record voltage and current data once every minute.
8. Data from both systems were concurrently recorded under identical environmental circumstances on June 11, 2025, when the measurements were conducted.
9. For additional processing and analysis, all of the data were stored in CSV format.

Every system had its own data logger, including the fixed panels and the solar tracker. The components and design of these two data loggers were identical. This was done to ensure that the data collection methods used by the two systems were identical. The two systems ran simultaneously, next to each other, and in the same sunlight and weather. This configuration made it simple to compare the data we gathered. We were able to determine which system performed better and gain a clear understanding of how much energy each one produced.

This approach helped eliminate any differences that might have come from the measuring equipment. It made the experiment more reliable and fair. Thanks to this careful setup, the comparison between the tracking system and the fixed system was based only on their actual performance and not on technical differences.

2.3 Materials and Tools

2.3.1 Tools

The following tools are used:

- **MATLAB** is a fourth-generation high-level programming language and interactive environment for numerical computation, visualization and programming. It allows matrix manipulations, plotting of functions and data, etc. It was used in this work for data analysis and for numerical computation.
- **Arduino Integrated Development Environment (IDE)** is a software that contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino hardware to upload programs and communicate with them. So, it was used in this work for the implementation of a code and its uploading in the data logger and solar tracker microcontroller.
- **Mendeley Software** is a reference manager and academic social network that can help you organize your research, collaborate with others online, and discover the latest research. More specifically, it was used to automatically cite references and generate bibliographies when writing this thesis.
- **FreeCAD** is a software used to design 3D models for engineering projects. It has tools to create and change shapes, and it helps to build mechanical parts on the computer. So, it was used in this work for the design of the solar tracker box and the data logger box.
- **Proteus** is a software that contains a window for drawing circuits, a message area to show errors, a toolbar with buttons for common functions, and a list of menus. It also allows you to write code for microcontrollers like Arduino and see how the circuit works on the computer. So, it was used in this work to simulate the circuit and test the code before uploading it to the data logger and solar tracker microcontroller.
- **Solidwork** is a 3D design software that helps people draw and build models of real objects on a computer. I used SolidWorks to design the mechanical mounting system for my solar tracker. This system holds the solar panel and lets it move to follow the sun. In SolidWorks, I created a 3D model of the frame, the rotating part, and the support arms for the linear actuator. I made sure everything was the right size to fit my solar panel and move correctly. The design was made to be strong and simple so I can build it with metal bars, screws, and bolts. This model helped me understand how the panel will move and how to fix the parts together.

- **KiCad** is a free software that helps people design electronic boards called PCBs (Printed Circuit Boards). I used KiCad to design the PCB for my solar tracker project. After I finished drawing the circuit in the schematic editor, I opened the PCB Editor in KiCad. There, I placed each part on the board, like the Arduino Nano, LDRs, relays, voltage regulator, and LCD screen. I made sure the parts were placed nicely with good space between them. Then I used the Route Tracks tool to connect the parts with copper lines. These lines carry the electricity from one part to another. When I was done, I checked everything to make sure the design was clean and correct. This layout will be used to make the real board.
- **Wokwi** is an online simulator where I can test Arduino projects before building them in real life. I used Wokwi to test my data logger. In this test, I used an Arduino Nano, a DHT22 sensor (to measure temperature and humidity), a DS3231 module (to keep the real-time clock), an ACS712 sensor (to measure current), a DC voltage sensor, and an SD card module (to save all the data). I connected all the parts and wrote a simple program. The Arduino collected the sensor data with the time and saved it on the SD card. This test helped me to make sure everything worked well before I built it in real life.
- **ThingSpeak** is a free online platform that helps people send and see sensor data on the internet. It is very useful for IoT (Internet of Things) projects. I used ThingSpeak to send and view my sensor data from the Arduino. In my project, the Arduino Nano collected data from sensors like the DHT22 (for temperature and humidity), the ACS712 (for current), and the voltage sensor. Then, using the right code and an internet connection, I sent this data to my ThingSpeak channel. On ThingSpeak, I could see the data as live graphs. This helped me know the values of temperature, humidity, current, and voltage from anywhere, just by checking my channel online.
- **Fritzing** is a free and simple software that helps create wiring diagrams for electronic projects. I used Fritzing to draw the connections for my data logger circuit. This helped me clearly see how each component should be connected. In my diagram, I connected the Arduino Nano to several important parts: the DHT22 sensor for measuring temperature and humidity, the ACSs712 sensor for measuring current, the DS3231 real-time clock to keep track of time, the SD card module for saving the collected data, and a voltage sensor to monitor voltage levels. This visual connection helped me and others follow the correct steps when building the real circuit.

2.3.2 Materials

2.3.2.1 Materials of Configurable Solar Tracker (CST)

The following Materials are used to make CST (Configurable Solar Tracker):

- **Arduino Nano**

Arduino Nano is a surface mount breadboard embedded version with integrated USB. It is a smallest, complete, and breadboard friendly. It has everything that Diecimila/Duemilanove has (electrically) with more analog input pins and onboard +5V AREF jumper. Physically, it is missing power jack. The Nano is automatically sense and switch to the higher potential source of power, there is no need for the power select jumper. Nano's got the breadboard-ability of the Boarduino and the Mini+USB with smaller footprint than either, so users have more breadboard space. It's got a pin layout that works well with the Mini or the Basic Stamp (TX, RX, ATN, GND on one top, power and ground on the other). This new version 3.0 comes with ATMEGA328 which offer more programming and data memory space. It is two layers. That make it easier to hack and more affordable[59].The figure 10 is the Arduino Nano.

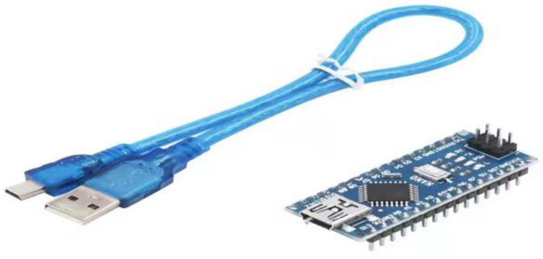


Figure 10: Arduino Nano

- **Light Dependent Resistor**

A Light Dependent Resistor (LDR) or a photo resistor is a device whose resistivity is a function of the incident electromagnetic radiation. Hence, they are light sensitive devices. They are also called as photo conductors, photo conductive cells or simply photocells.

They are made up of semiconductor materials having high resistance. There are many different symbols used to indicate a LDR, one of the most commonly used symbol is shown in the figure below. The arrow indicates light falling on it.

when the photons fall on the device, the electrons in the valence band of the semiconductor material are excited to the conduction band. These photons in the incident light should have energy greater than the band gap of the semiconductor material to make the electrons jump from the valence band to the conduction band. Hence when light having enough energy strikes on the device, more and more electrons are excited to the conduction band which results in large number of charge carriers. The result of this process is more and more current starts flowing through the device when the circuit is closed and hence it is said that the resistance of the device has been decreased. This is the most common working principle of LDR[60]. The figure 11 above presents the LDRs.

Figure 11: Light Dependent Resistors (LDRs)

- **Relays**

Micro Relay Switches: A relay switch (12v 20a relay) is an electrically operated switch that is used in applications that require the control of a circuit by a low-power signal, where the control and controlled circuits must be electrically isolated from one another. Relay circuit switches are found in most vehicles driving along our roads today.

5 Pin Automotive Relay: They are most commonly used to enable a low amperage circuit switch On or Off a higher amperage circuit. The most frequent example of this is the switching on of the vehicle's head lights.

Circuit Safety: It is unadvisable to hook up directly the headlights to the headlight switch as this could exceed the amperage rating of the switch. In such an event, the unwanted risk of causing an electrical fire or damaging cable wires may be encountered.

Micro Relay Switches - Multiple Switching: Relays can also be used to facilitate the switching of multiple components at the same time using a single output. A single output connected to multiple relays, like this 12v 20a relay 5 pin, will allow you to open continuity and/or close continuity simultaneously - a very useful function.

Looking for a 5 pin relay wiring diagram or 5 pin micro relay diagram? Check out our 5 pin relay diagram, 5 pin mini relay wiring diagram, mini relay pinout schematics above in product description [61]. The figure 12 is showing the relays.

Figure 12: Micro Relay Switches

- **Voltage Regulator**:

A voltage regulator is used to regulate voltage levels. When a steady, reliable voltage is needed, then the voltage regulator is the preferred device shown in figure. It generates a fixed output voltage that remains constant for any changes in an input voltage or load conditions. It acts as a buffer for protecting components from damages. A voltage regulator is a device with a simple feed-forward design and it uses negative feedback control loops[62]. The figure 13 is the image of Regulator.

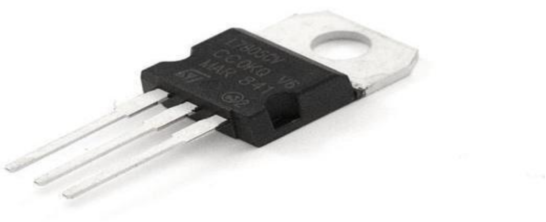


Figure 13: Voltage Regulator

- **Capacitor:**

Capacitors are electronic components that store, filter and regulate electrical energy and current flow and are one of the essential passive components used in circuit boards. Capacitors are primarily used for storing electrical charges, conducting alternating current (AC), and blocking or separating different voltages levels of direct current (DC) source[63]. The figure 14 above is the image of Capacitor.

Figure 14: Capacitor

- **Transistor:**

A transistor is a miniature semiconductor that regulates or controls current or voltage flow in addition to amplifying and generating these electrical signals and acting as a switch or gate for them. Typically, transistors consist of three layers, or terminals, of a semiconductor material, each of which can carry a current. Transistors are crucial components of modern electronics. When working as an amplifier, a transistor transforms a small input current into a bigger output current. As a switch, it can be in one of two distinct states on or off to control the flow of electronic signals through an electrical circuit or electronic device [64]. The figure 15 is the transistor.

Figure 15: Transistor

- **Resistors:**

The resistor is a passive electrical component that creates resistance in the flow of electric current. In almost all electrical networks and electronic circuits they can be found. The resistance is measured in ohms (Ω). An ohm is the resistance that occurs when a current of one ampere (A) passes through a resistor with a one volt (V) drop across its terminals. The current is proportional to the voltage across the terminal ends[65]. The figure 16 is the resistor.

Figure *16:* Resistor

- **Boost Converter**

A boost converter is a small electronic circuit that makes low voltage become higher. It works by storing energy in a coil (called an inductor) when a switch is on. When the switch turns off, the coil sends the energy to the output. This helps give more voltage. The circuit has parts like a switch, diode, coil, and capacitor. The boost converter is useful when we need more voltage than the battery gives, like in solar or LED systems. The output voltage depends on how long the switch stays on or off. The above figure 17 is the example of boost converter.

Figure 17 : Boost Converter [66]

- **Liquid Crystal Display (LCD):**

Display devices visually present the processed data. Among other types of displays are LCD (liquid crystal display) monitors, popular among electronic projects due to being inexpensive and reasonably effective. LCDs come mainly in two (2) varieties: the common LCD and the LCD with I2C interface (LCD I2C). Working with the original LCD means many wires among which setup stands cumbersome. The figure 18 is Liquid Crystal Display (LCD).

Figure 18: Liquid Crystal Display (LCD)

2.3.2.2 Materials of Data Loggers

The following Materials are used to make CST (Configurable Solar Tracker):

- **Arduino Uno**

The Arduino UNO is a popular microcontroller board used for building electronic systems. It is easy to use, low-cost, and programmable. The board is based on the ATmega328 microcontroller and contains 14 digital input/output pins, 6 analog input pins, and a USB port for programming. It can control LEDs, sensors, motors, and other electronic devices. In this project, the Arduino UNO is used as the brain of data logger. It reads data from sensors, manages real-time tracking, and stores the values on an SD card. The board runs on 5V and can be powered using a battery or a DC power supply. The figure 19 is the Arduino Uno.

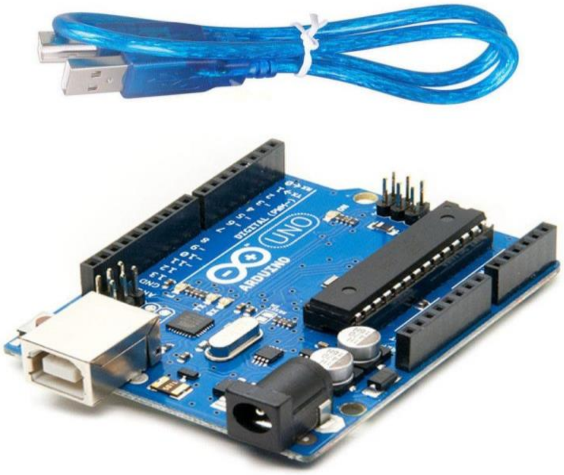


Figure 19 : Arduino Uno

- **Single-Sided Copper-Clad PCB (20×15 cm)**

It is a Printed Circuit Board (PCB) made of epoxy, with copper on one side only, and the size is 20 cm by 15 cm. It is commonly used for prototyping electronic circuits**.** The figure 20 below is Single-Sided Copper-Clad PCB (20×15 cm).

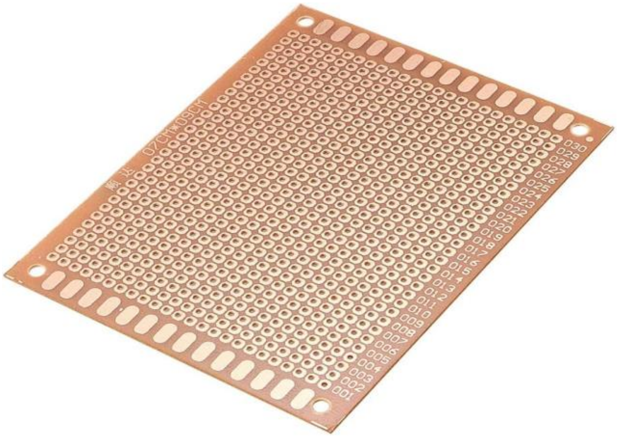


Figure 20 : Single-Sided Copper-Clad PCB (20×15 cm)

➢ The ACS712 Sensor

The ACS712 is a small sensor that helps measure electric current. It can measure both AC and DC current. It uses a special method called the Hall effect to feel the magnetic field from the current and turn it into a voltage. This voltage goes to a microcontroller like an Arduino. The sensor is safe, easy to use and works in many projects like motor control, solar systems and power monitoring. The figure 21 is the ACS712 example.

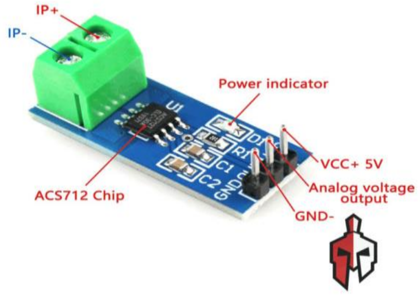


Figure 21 : ACS712 Sensor[67]

➢ DCVS30-H16S8 (Voltage Sensor)

The DCVS30-H16S8 is a small sensor that helps measure voltage. It takes high voltage from a solar panel or battery and changes it into a smaller voltage that an Arduino can read. This helps the system know how much voltage is coming from the source. The sensor is easy to connect, works well with microcontrollers, and is useful in solar projects and other electronic systems where safe voltage checking is needed. The figure 22 is the image of voltage sensor.

Figure 22 : DCVS30-H16S8 Voltage Sensor

➢ SD card Module

The SD module library is used in Arduino projects to read and write data on SD cards using SPI communication. It supports common file systems like FAT16 and FAT32 and allows storing sensor data in text files. In this project, the library was used to save measurements such as current, voltage, temperature, humidity, and timestamps onto an SD card. The Arduino Uno communicated with the SD module through SPI pins, and the data was stored in files like "log.txt" for later analysis. This helped monitor the solar tracking system's performance and provided valuable information for results and discussion in the thesis. The figure 23 below is the image of SD card module.

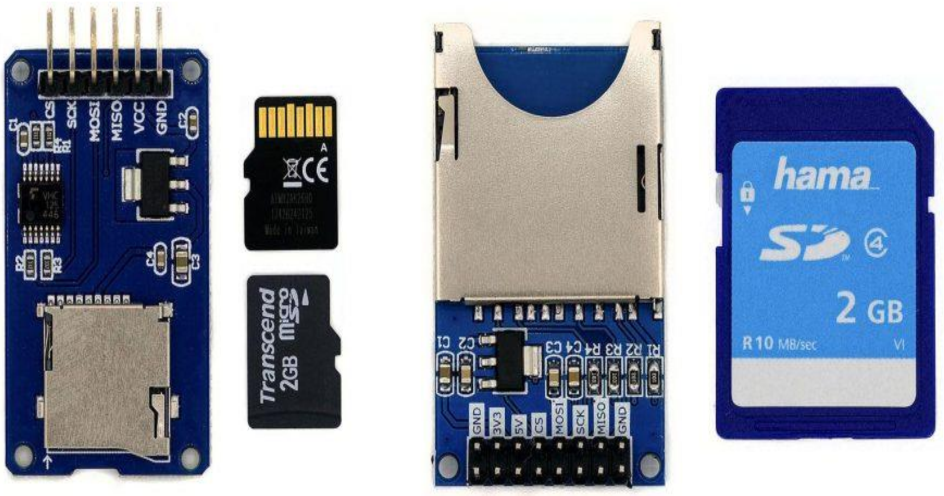


Figure 23 : SD card Module

- **Real-Time Clock (RTC) RtcDS1302**

A Real-Time Clock (RTC) is a small device that keeps the correct time, even when the main power is off. It uses a small battery to keep working all the time. The RTC has a crystal that helps it stay accurate. It is used in many electronic projects to remember the time and date. In our project, the RTC was used to record the exact time when data (like voltage, current, or temperature) was saved. It helped the system know the date and time of each measurement, even when the power was off.

Figure 24 : Real-Time Clock (RTC) RtcDS1302

The figure 24 above is the RTC.

2.4 Methods

The following are the main four (4) steps taken to achieve the specific objectives of this thesis:

i Review of Literature and Technology Assessment

An exhaustive review of the literature was conducted to assess the present technologies and methods employed in solar tracking systems. Solar tracking systems were selected based on their relevance and adaptability to the environmental and climatic context of Ouagadougou, Burkina Faso. This step tackled specific objective 1.

ii Selection and Integration of Electronic Components

In view of the literature study results, appropriate electronic components (microcontrollers, sensors, actuators, etc.) were selected. Components were selected to allow both single and dual-axis solar tracking configurations and to operate in the stringent Sahelian conditions. Besides, the choice should allow for easy integration and further upgrades of the system.

iii Development of the Configurable Solar Tracking System and Data Loggers

This step covers the design, prototyping, and implementation of a configurable solar tracking system (single or dual axis). Two independent energy systems were set up:

- One equipped with the developed solar tracker
- One using a traditional fixed solar panel system

Two specific data loggers were developed to monitor all the relevant parameters (i.e., voltage, current, Temperature and humidity) of both systems in real time. The development was targeted toward low cost and local.

iv Experimental Data Collection and Comparative Analysis

Following the system development, experimental data were collected from both installations and then analyzed to evaluate performance. This step addressed objectives 2 and 3 by comparing the energy output of the tracking and fixed systems under identical environmental conditions. The data were carefully recorded to make sure the results were accurate. This analysis helped to show which system produced more energy during the test period. The comparison was made under the same weather and sunlight conditions. This made the results fair and reliable. The findings will help improve solar energy use in Ouagadougou. For this methodology, we followed the flow chart as showing the figure 25.

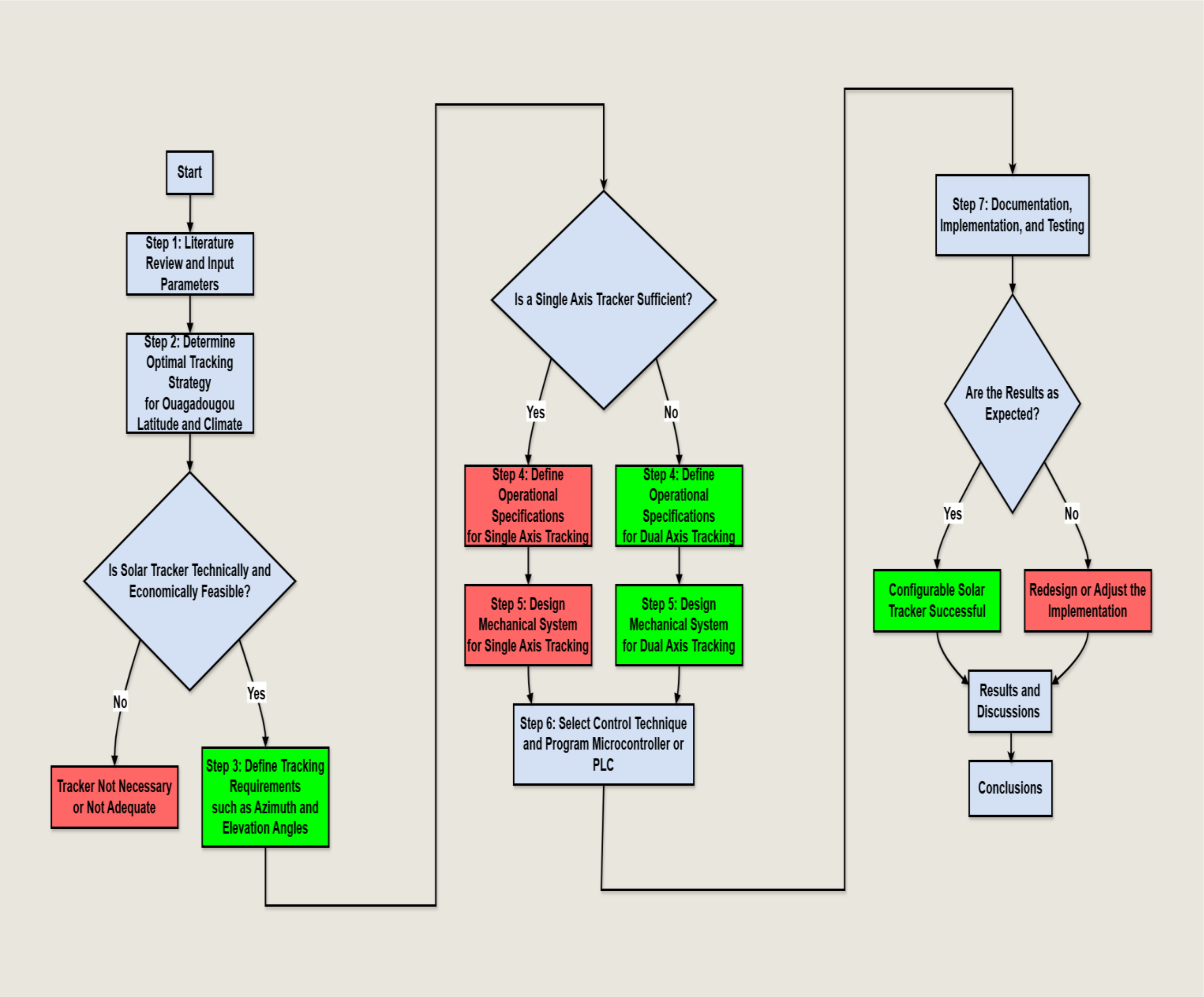


Figure 25 : Flow Chart of the Methodology process

2.4.1 Data cleaning

The data cleaning was done to remove unwanted data from the dataset collected during the one-day experiment carried out in Ouagadougou. During this experiment, minute-based data of current and voltage for both the dual-axis solar tracking system and the fixed-panel system were first recorded. But, some of these data were affected by sensor errors or technical issues during the recording process. Thus, data containing missing values (NaN), zero values, or inconsistencies due to sensor malfunction were identified and removed before analysis. Indeed, it was expected that the entire day's data would be usable. However, due to some sensor malfunctions and recording interruptions, only valid data recorded during daylight hours could be used, as the night period was not considered in the experiment. Among the collected data, only a portion met the quality required for precise energy calculations, and this, after eliminating the erroneous readings. The remaining faulty values were discarded as they did not reflect the actual energy production.

After the data cleaning process, the dataset used to calculate the energy produced by the dual-axis tracker and the fixed-panel system during the day in Ouagadougou is presented in the following analysis.

2.4.2 Calculation of key variables (power and energy) for comparison

i Power calculation

The instantaneous electrical power PPP produced by each panel was calculated using the basic electrical power formula:

$$\mathbf{P} = \mathbf{V} \times \mathbf{I} \qquad [1]$$

Where:

- V is the voltage in volts (V)
- I is the current in amperes (A)
- P is the power in watts (W)

This computation was done for each minute based on the collected data.

Energy Calculation

Given that data was collected at one-minute intervals, the energy produced during each interval was calculated using:

ii Energy Calculation

Given that data was collected at one-minute intervals, the energy produced during each interval was calculated using:

$$\mathbf{E} = \frac{\mathbf{P \times \Delta t}}{\mathbf{3600}} \qquad [2]$$

Since Δt = 60 seconds, this simplifies to:

$$\mathbf{E} = \frac{\mathbf{P}}{\mathbf{60}} \qquad [3]$$

Hence, the energy in watt-hours (Wh) for each time step wa lculated as:

$$\mathbf{E} = \frac{\mathbf{P\ x\ I}}{\mathbf{60}} \qquad [4]$$

The total daily energy output for each system was then obtained by summing nergy values across all time intervals:

$$\boldsymbol{f(t)} = \sum_{t=1}^{t} \mathbf{E(t)} = \frac{\mathbf{P(t).I(t)}}{\mathbf{60}} \qquad [5]$$

iii Comparative Analysis

To assess the performance difference between the tracker and fixed systems, the percentage increase in energy production of the solar tracker over the fixed panel was calculated using the formula:

$$\boldsymbol{\eta} = \frac{\mathbf{Et - Ef}}{\boldsymbol{Ef}} \qquad [6]$$

Where:

- Et is the total energy produced by the tracker system
- Ef is the total energy produced by the fixed system

This metric quantifies how much more efficient the solar tracker was in converting solar energy to electrical energy over the same period.

2.4.3 Efficiency Criteria for Solar Energy Optimization

As solar energy becomes a vital alternative in energy production, the optimization and proper management of photovoltaic (PV) systems have gained increasing attention around the world. Yet, there are now many opportunities to improve and better manage PV energy output. One particular opportunity for optimization is the better control and configuration of solar tracking systems. Many efficiency requirements to improve PV performance exist. In this section, an inventory of some of them is provided.

- According to [68],using a solar tracking system instead of a fixed photovoltaic installation is a reliable way to improve energy production. Their study showed that solar tracking systems capture more sunlight throughout the day, especially during morning and evening hours when the sun’s angle is lower.
- Naraghi and Atefi (2022) examined how environmental dust affects solar panels in West Africa during the Harmattan season. They found that the accumulation of dust on photovoltaic panels, known as soiling, causes a significant drop in power generation, particularly in regions close to the Sahara Desert[69].
- In reception of various new technologies and solutions, the global deployment of solar photovoltaics systems is seeing tremendous growth in recent times. However, elevated temperatures significantly reduce PV module efficiency. As highlighted in recent experimental studies, high PV module temperatures caused by solar radiation and ambient conditions lead to lower electrical performance due to increased internal carrier recombination and reduced open-circuit voltage[70] .
- One approach to improving solar panel efficiency is by integrating sensors and data loggers to monitor performance, such as using LDRs for sun tracking and INA219 sensors for digital current and voltage readings[71].
- Implementing Maximum Power Point Tracking (MPPT) techniques can significantly improve the efficiency of solar panel systems by maximizing voltage and current output (IoT-Based Solar Monitoring Study, 2025). For instance, using MPPT alongside IoT tools allows real-time monitoring of parameters like light intensity, temperature, and energy output on an LCD screen, while also sending warnings for system faults.
- In their study on PV panel performance under urban constraints, researchers observed that shading from surrounding objects and accumulated soil significantly reduces energy output, especially in dry and semi-arid regions like Morocco[72].

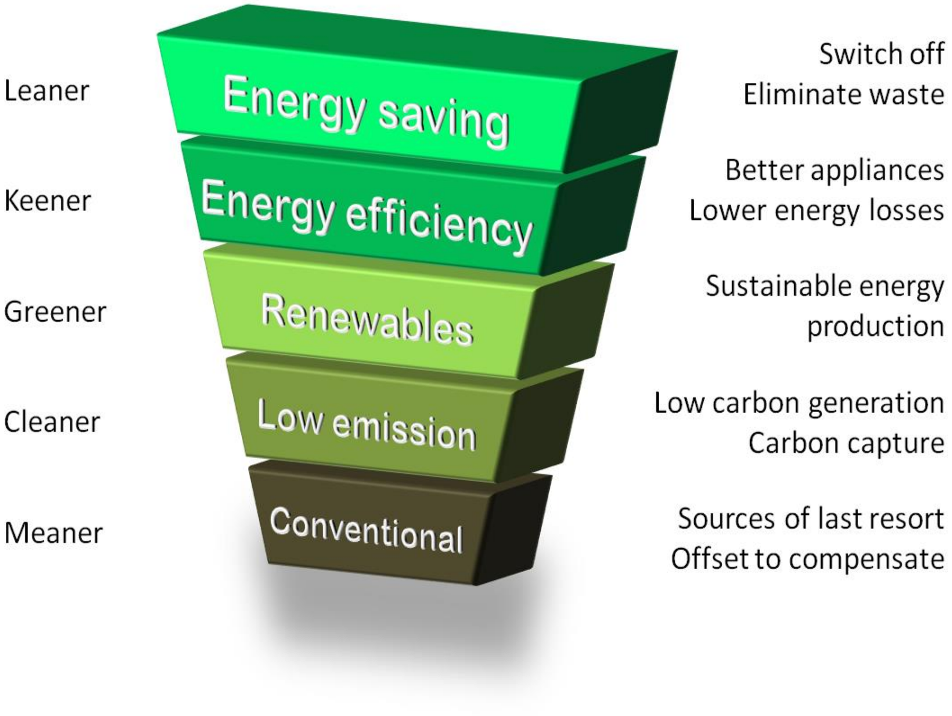


Figure 26: The Energy Hierarchy with the most favored options at the top

Source:[73]

Therefore, we propose some efficiency requirements for the smart solar tracking system so that for optimum photovoltaic energy output in Ouagadougou:

i Let the user configure the tracking system for a single-axis or dual-axis operation according to the available resources and installation environment.

ii Use a light sensor (LDR) to follow the path of the sun during the day so that the panel's surface is turned toward the maximum sunlight.

iii Have a data logger to record current, voltage, light intensity, and temperature every 5 minutes, so energy performance can be followed.

iv Give an alert and warning on the LCD display in case of any fault, low sunlight, or any other condition that hampers the working efficiency of the system.

v Electric-actuators should move the panels, choosing those actuators which are locally available, easy to control, durable to Sahelian weather conditions.

vi Track energy performance of the tracking system with respect to a fixed PV panel, setup on-site, for effective comparison of energy output. The figure 26 is the energy hierarchy.

2.4.4 Development of Solar tracker

2.4.4.1 Selection and Analysis of Electronic Components

In my project, we picked each electronic part carefully. We looked for components that are available in Burkina Faso or West Africa, that use less electricity, and that are not expensive. We also learned how each part works and how it helps the system.

- **Voltage Regulator – 7805 (U2)**

We used the 7805 voltage regulator to give a fixed 5V output (VO) to important parts like the Arduino Nano, the light sensors (LDRs), and the LCD display. These parts needed 5V to work well. But my battery gave 12V, so We needed a way to lower the voltage. The 7805 helped me make the voltage safe and stable.

On the PCB, we connected pin 1 (VI) of the regulator to the +12V input and to the positive side of capacitor C4. We linked pin 2 (GND) to ground, and it also went to the negative sides of capacitors C4 and C5. Then, we connected pin 3 (VO) to give +5V output to the Arduino, the LCD module, and the I/O Expander (PCF8574).

chose this part because it was cheap, easy to find in local markets in Burkina Faso and West Africa, and it used little energy. It also worked well with small devices. On the PCB, We placed the regulator close to the power input to help send clean power to the rest of the system safely.

- **Capacitors – 100µF and 1000µF (C1, C2, C3, C4, C5)**

The circuit has five capacitors that help keep the power stable and safe. The 100µF capacitors (C1, C4, and C5) remove small noise in the voltage. Capacitor C1 is placed at the input of the DC-DC converter, between +12V and GND. C4 is connected to the input of the 7805 voltage regulator, with its positive side on VI (12V) and its negative side on GND. C5 is connected to the output of the 7805, with its positive side on VO (5V) and its negative side on GND. These capacitors help the regulator work better. The 1000µF capacitors (C2 and C3) store extra energy and give it when needed. C2 is connected at the output of the DC-DC converter, between +12V and GND, to support other parts like the voltage regulator. C3 is placed near the +5V line of the Arduino Nano, between +5V and GND, to keep the voltage stable when sensors or the Arduino need more current. These capacitors are small, low-cost, and very helpful in protecting the whole system.

- **Resistors (R1 to R11)**

Several resistors are placed in the circuit to control the flow of current. Resistors R1 to R4 (1kΩ each) are connected to the bases of four transistors. These transistors are used to drive the relays that control the linear actuator. This helps the actuator move safely when the system sends a signal. Resistors R8 and R9 are connected to two LDRs (light sensors). Together, they form voltage dividers. This allows the Arduino to read the difference in light from the sun, which helps the solar tracker follow the sunlight in the right direction.

- **LED D5**

We added a red LED to show that the system is powered. It is placed close to the voltage regulator and resistor R7. This LED helps me see if the board is working without using a screen. It is simple but useful.

- **Microcontroller (Arduino Nano - NANO1)**

The Arduino Nano is the main controller of the system. It is placed in the middle of the board, inside the big rectangle with many pins. This makes it easy to connect wires from other parts, like sensors and power lines. The Nano is small and uses little power, which is good for simple and low-cost projects. It connects to +5V and GND from the 7805 regulator to work safely. The inputs and outputs from the Nano are used to read sensor values and control other parts. This board is also easy to program and can be found in many markets in Africa, so it is a smart choice for local projects.

- **Display (LM016L LCD and PCF8574 I/O Expander - LCD2 and U1)**

The LM016L LCD was used to show important information, like the status of the system or the direction of sunlight. To make the connection easier, I added the PCF8574 I/O expander. This small chip allowed the LCD to use only two pins from the Arduino Nano, instead of many. The LCD and the expander were connected to the Arduino Nano using the I2C method. I connected the GND of the LCD to the GND of the Arduino Nano, and VCC to VIN. Then, I connected SDA to pin A4, and SCL to pin A5. This way, the display could talk to the Arduino with just these few wires. These parts are cheap and easy to find in markets or shops around schools and universities in West Africa.

- **Light Sensors – LDR1 to LDR4**

The LDRs (Light Dependent Resistors) are the sensors that help the system find the sunlight. They change their resistance when the light is strong or weak. We connected each LDR with a resistor, like R8 and R9, to make voltage dividers. These dividers help the Arduino read the light level. We used four LDRs in total two facing East and West, and two facing North and South. This helps the Arduino know where the sun is in the sky. When it sees more light on one side, it sends a signal to the relays. The relays turn on the linear actuator to move the solar panel toward the sun. This system is smart, low-cost, and works well in places like Burkina Faso or other parts of West Africa.

- **Battery – 12V (BAT1)**

The 12V battery powers our whole system. It gives enough energy for the Arduino, relays, and actuators. We picked it because 12V batteries are common here. They are used in solar kits and motorbikes. They are easy to charge and replace when needed.

- **Diodes – 1N4007 (D1, D2, D3, D4)**

We included four 1N4007 diodes to protect the system. These diodes stop the current from going the wrong way, which can damage the components. We connected each diode to one of the four transistors that control the relays. This setup helped keep the transistors safe when the relays turn on and off. The 1N4007 diodes are strong, very useful, and easy to find in most local electronic shops.

- **Transistors – BC547 (Q1, Q2, Q3, Q4)**

We used BC547 transistors to control the relays. They act like small switches, turning things on or off when the Arduino tells them. Each transistor is connected to one of the relays, and we used resistors (R1 to R4, 1kΩ) between the Arduino and the base of each transistor to control the current. We also added 1N4007 diodes to each transistor to protect them from back current when the relays turn off. These transistors help the Arduino send a small signal that activates the relays, which then move the linear actuators. We selected these transistors because they are easy to use, cheap, and perfect for light loads.

- **Relays – RL1 to RL4 (12V)**

To manage the linear actuators, we connected four 12V relays. Each relay is controlled by a BC547 transistor. The Arduino sends a signal through a resistor (R1 to R4) to the transistor's base. When the transistor receives the signal, it switches on the relay. We also added 1N4007 diodes to each transistor to stop back current from damaging the system. When the relay is activated, it powers the linear actuator to move. These relays are strong enough for big loads, simple to connect, and often used in local solar or motor projects. They are easy to find in West Africa and do not use much energy.

2.4.4.2 Simulation in Proteus Software

After completing the selection and analysis of the electronic components, we moved on to simulate the solar tracking system using Proteus software. This step was very important to test the overall operation of the circuit before building it physically. It helped me make sure that all components worked well together and followed the logic I programmed into the microcontroller.

To make the simulation realistic, we first added the Arduino Nano, the LCD with I2C module, and the linear actuators into the Proteus workspace. These were the most important parts of the system, and their libraries allowed me to simulate their real behaviors.

The connections between the components were made as follows:

- A 12V DC power supply is connected to a 7805 voltage regulator, which gives a stable **5V** output.
- This 5V powers the Arduino Nano, the LDR sensors, and the LCD module.
- Two LDRs are used to detect light on both sides of the solar panel. Each LDR is connected with a 1kΩ resistor in a voltage divider setup. The middle wires go to analog pins A0 and A1 of the Arduino.
- The Arduino's digital pins D2 to D5 are connected to the base pins of BC547 transistors through 1kΩ resistors. These transistors act as switches to control four relays.
- The relays are connected to the linear actuators via terminal blocks (J6 and J7). These actuators move the solar panel horizontally and vertically to follow the sun.
- To protect the circuit, 1N4007 diodes are connected across the relay coils.
- The LCD display (using an I2C interface) is connected to SDA (A4) and SCL (A5) pins of the Arduino. It shows the voltage and current produced by the solar panel during the simulation.

After wiring everything in Proteus, we uploaded the Arduino code (**.** hex file) to the virtual Arduino Nano. When we started the simulation, we observed how the panel responded when one LDR received more light than the other. The Arduino sent signals to the relays, which activated the linear actuators to move the panel toward the light source. At the same time, the LCD displayed the real-time electrical values.

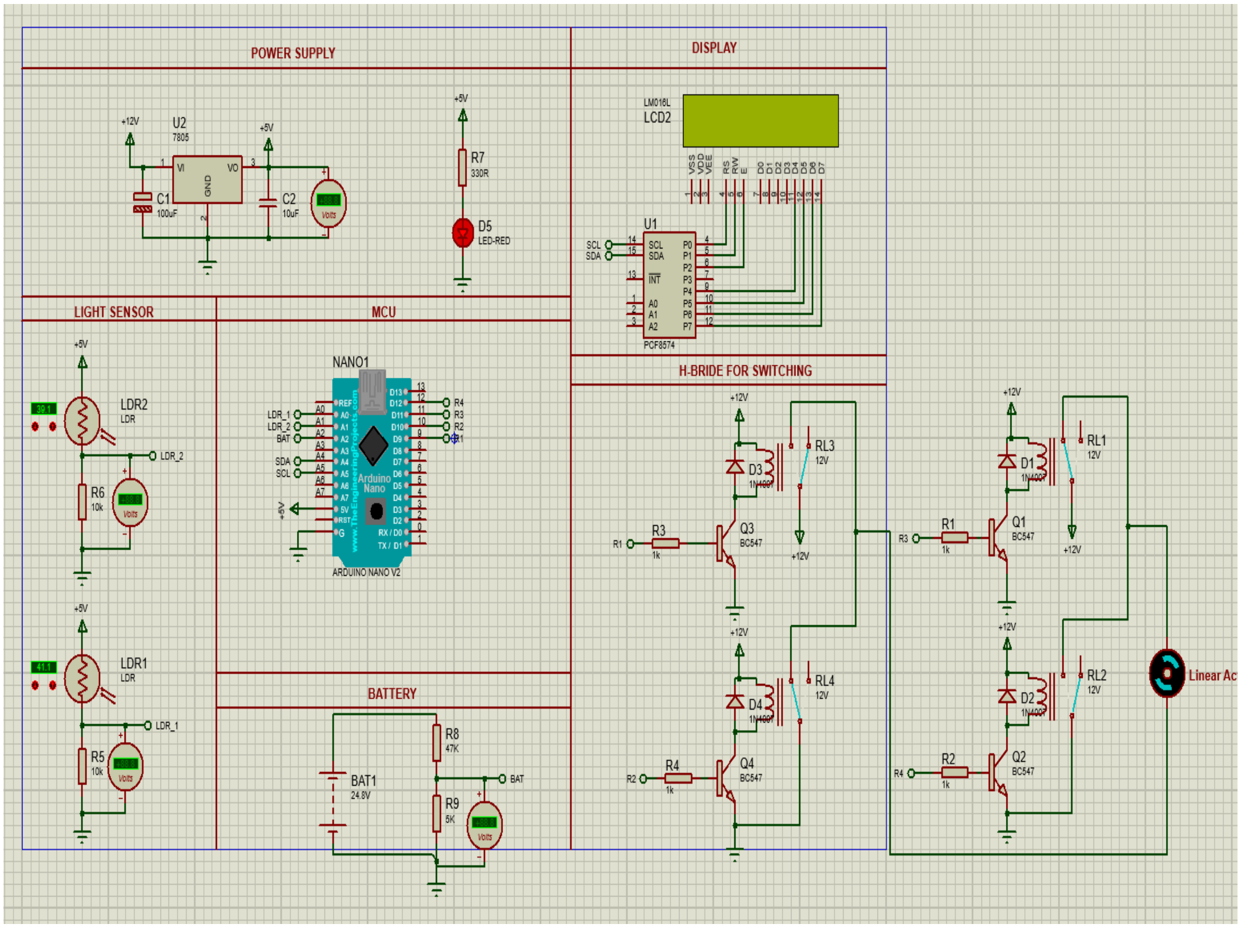
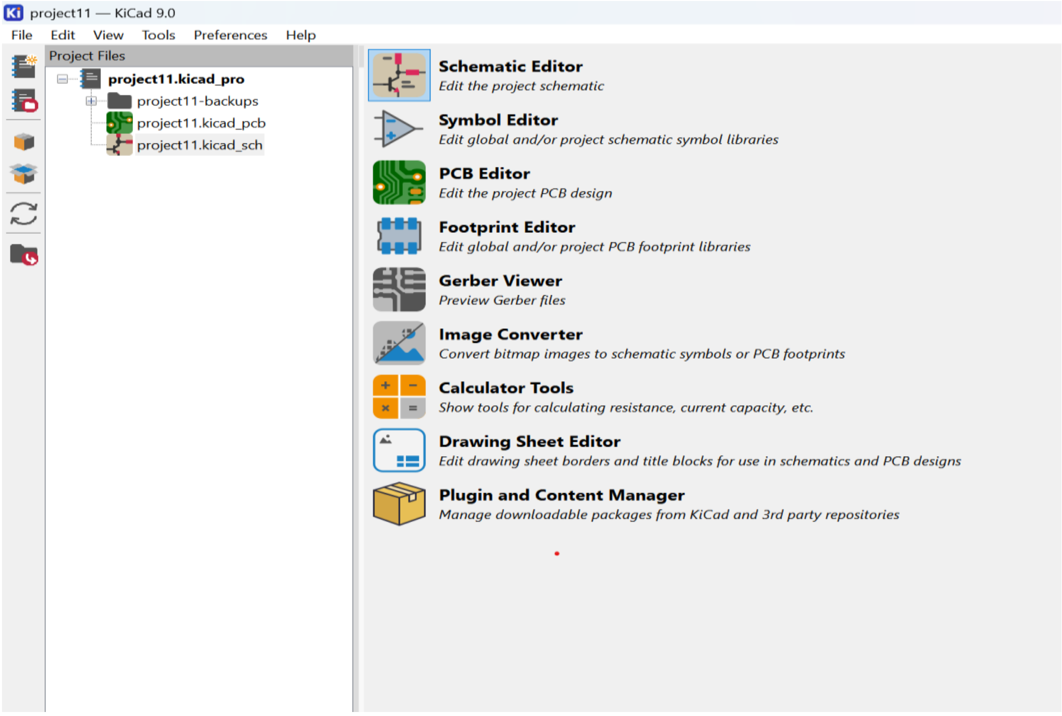


Figure 27: Screenshot of the Proteus Simulation

Before building the physical solar tracking system, we used Proteus software to create a complete simulation of the hardware. This included all the key components such as the Arduino Nano, LDR sensors, relays, linear actuators, and the I2C LCD display. During the simulation, we uploaded the Arduino program to check how the system would behave in response to changing light conditions. The relays correctly activated the linear actuators to adjust the solar panel's position, and the LCD displayed real-time voltage and current values from the solar panel. This step was very helpful because it allowed me to verify the circuit design, correct small mistakes, and ensure smooth operation before moving to physical assembly. It saved both time and effort and gave me confidence in the success of the system. The image below shows the full simulation as designed in Proteus. The figure 27 is Screenshot of the Proteus Simulation.

2.4.4.3 PCB Design and Fabrication

After I tested my solar tracking circuit in Proteus and saw that everything was working, we decided to design a real physical board called a Printed Circuit Board, or PCB. A PCB is a hard, flat board where electronic parts are connected together in a clean and strong way. To do this, we used software called KiCad, which is free and made for creating circuits and PCBs. KiCad is a powerful tool that helps people draw electronic circuits, design how the parts will be arranged on the board, and then prepare files that factories use to make real PCBs. It has many features like a schematic editor (to draw the circuit), a PCB layout tool (to place and connect the parts), and a 3D viewer (to see how the final board will look). The image below shows what the KiCad software looks like when designing a circuit



project11.kicad_pro
project11-backups
project11.kicad_pcb
project11.kicad_sch

Schematic Editor
Edit the project schematic

Symbol Editor
Edit global and/or project schematic symbol libraries

PCB Editor
Edit the project PCB design

Footprint Editor
Edit global and/or project PCB footprint libraries

Gerber Viewer
Preview Gerber files

Image Converter
Convert bitmap images to schematic symbols or PCB footprints

Calculator Tools
Show tools for calculating resistance, current capacity, etc.

Drawing Sheet Editor
Edit drawing sheet borders and title blocks for use in schematics and PCB designs

Plugin and Content Manager
Manage downloadable packages from KiCad and 3rd party repositories

Figure 28: KiCad Window While Designing My Circuit

When I opened KiCad, I saw a clean and helpful interface. At the top, there were menus like File, Edit, and Tools to manage my project. On the left side, we saw the files created, such as project11.kicad_sch, where we drew the circuit; project11.kicad_pcb, where I designed the board layout; and project11.kicad_pro, which was the main project file. There was also a backup folder. In the center, we saw buttons that opened different tools like the Schematic Editor, PCB Editor, 3D Viewer, and Gerber Viewer. These tools helped me create, check, and prepare my electronic circuit to become a real printed circuit board. The figure 28 is KiCad Window While Designing My Circuit.

- **Drawing the Circuit – Schematic Editor**

After we set up our project in KiCad, the first thing we did was draw my full circuit in the Schematic Editor. This part is like making a plan on paper that shows how all the electronic components are connected. we added the main components that we used for our solar tracker project. These were:

- Arduino Nano – the brain of the system,
- LDRs (Light Dependent Resistors) – to detect the direction of sunlight,
- Linear actuator motor – to move the solar panel,
- 7805 voltage regulator – to keep the voltage stable,
- BC547 transistors – to help switch the motor on and off,
- Relays – to control the high power part of the circuit,
- Diodes, resistors, capacitors – for safety and proper flow of current,
- 16x2 LCD display – to show the system status like movement and light direction.

Then, we used the wire tool to connect all these parts together, just like joining lines between dots. we made sure the connections were correct and clean. After we finished, KiCad saved our circuit drawing as a file ending in project11.kicad_`sch`. Below is the schematic I designed in KiCad's Schematic Editor for my solar tracking system. The figure 29 below is Schematic Diagram of the Solar Tracking System in KiCad.

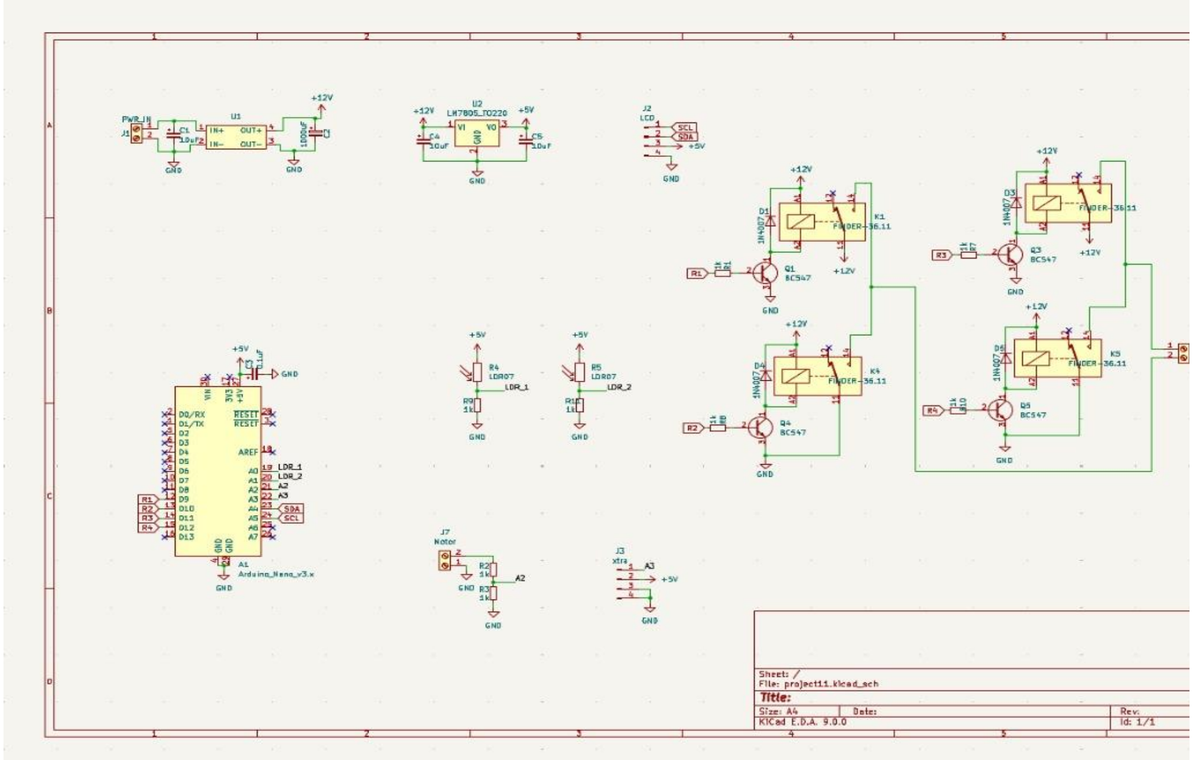


Figure 29: Schematic Diagram of the Solar Tracking System in KiCad

2.4.5 Development of Data Loggers

2.4.5.1 Selection and Analysis of Components

In my data logger project, we carefully selected each electronic component based on three main criteria: availability in Burkina Faso or West Africa, low power consumption, and low cost. we also took the time to understand how each component works and how it contributes to the system's performance.

- **Microcontroller – Arduino Uno (U1)**

  We used an Arduino Uno as the central controller of the data logger. It was ideal for our project because of its small size, low energy use, and compatibility with different sensors and modules. The Uno was responsible for reading data from the current, voltage, temperature, and humidity sensors, keeping track of the time using the RTC, and saving everything to an SD card. It connects to a 5V regulated power source from the battery. The Uno is widely available in electronics markets in Burkina Faso, making it a smart and accessible choice.

- **Current Sensor – ACS712 (5A Model)**

  To measure the current from the solar panel, we used the ACS712 current sensor. This sensor outputs a voltage that changes depending on the current passing through it. We connected its VCC to 5V, GND to ground, and the output to analog pin A0 of the Arduino. This allowed the Arduino to read the current and calculate power generation. We chose the 5A version because it matched the expected current range and had good accuracy. The ACS712 is easy to use, consumes little power, and is available in local stores.

- **Voltage Sensor – DCVS30-H16S8**

  To measure the voltage from the solar panel, we used a DCVS30-H16S8 sensor. It converts high input voltages down to safe levels for the Arduino's analog input. We connected its Vin to the positive line of the solar panel, GND to ground, and Vout to analog pin A1. This sensor allowed the Arduino to monitor the real-time voltage of the panel safely. We picked this sensor because it works well with 12V sources and is available from regional suppliers or online stores that ship to West Africa.

- **Temperature and Humidity Sensor – DHT22**

  The DHT22 sensor helps the system record the environment's temperature and humidity. We connected its data pin to digital pin 2 on the Arduino, with power supplied by the 5V line. The

DHT22 is simple, low-cost, and accurate enough for basic weather logging. It is commonly used in schools and student projects in the region, making it easy to find and replace.

- **Real-Time Clock (RTC) – DS3231**

To record accurate timestamps for each data entry, we used a DS3231 RTC module. It communicates with the Arduino using I²C, connected through pins A4 (SDA) and A5 (SCL). The DS3231 also has its own battery, so it keeps time even when the system is off. We selected this module because it is reliable, uses very little power, and helps create precise logs of voltage, current, temperature, and humidity values over time.

- **SD Card Module**

The SD card module was used to store all the logged data. It connects via SPI using pins 10 (CS), 11 (MOSI), 12 (MISO), and 13 (SCK) on the Arduino Nano. We used a microSD card formatted in FAT32 to make data retrieval easy. This module was chosen because it is cheap, simple to use, and compatible with the Arduino SD library. It is also widely available and used in many academic projects.

- **Battery-9V**

The solar data logger is powered by a 9V battery, which is stepped down to 5V using a DC-DC buck converter. This 5V output is necessary for components like the Arduino Nano, sensors, RTC, and SD card module. The buck converter was chosen for its high efficiency, voltage stability, and better battery life, making it ideal for low-cost, off-grid applications.

2.4.5.2 Simulation in Wokwi and Proteus

The simulation of the system was conducted using both Wokwi and Proteus to ensure the functionality and reliability of the design before physical implementation. Wokwi was particularly useful for testing the Arduino Uno code and verifying the interaction between the connected components, including the ACS712 current sensor, DC voltage sensor, DHT11 temperature and humidity sensor, RTC module, and the SD card module. It provided a virtual environment where the logic and data flow could be observed and debugged effectively. On the other hand, Proteus was used to simulate the complete electrical wiring of the system. It allowed for visual verification of connections and behavior of each component under simulated conditions, ensuring that the circuit would work as intended in real life. These two simulation tools complemented each other by combining software logic testing with hardware-level verification. Here is Simulation of Data Logger in Proteus as showing in figure 30.

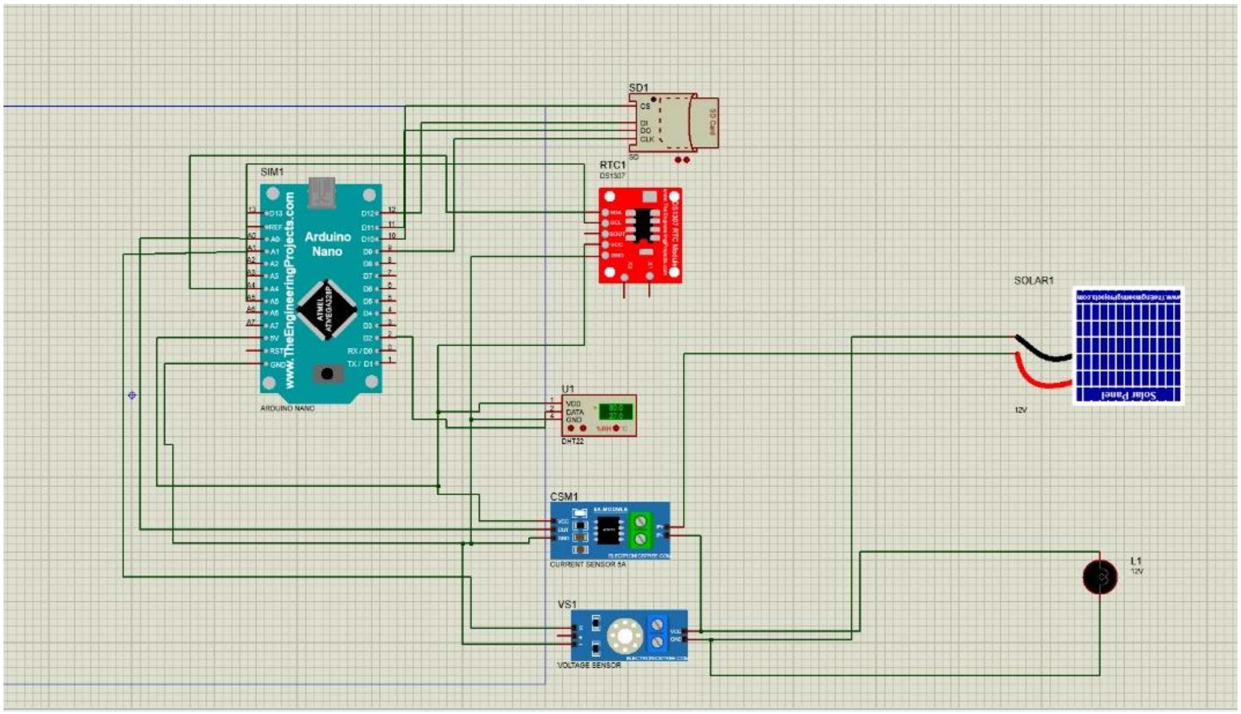


Figure 30: Simulation of Data Logger in Proteus

2.4.5.3 Breadboard Test

When we finished the simulation, we placed all the electronic parts on a breadboard so as to check if the system worked in reality. This step was very important to attest to the reliability and accuracy of the theoretical design. We very carefully duplicated the wiring as it was in the simulation environment by using an Arduino Uno as the central controller connected to various sensors (including the LDRs for light detection, and INA219 for voltage and current measurement), plus an SD card module for data-logging. The breadboard was a temporary, flexible platform that was vitally important for the speedy detection and troubleshooting of problems such as incorrect pin connections, unstable voltage levels, or unreliable sensor outputs. We monitored the sensor readouts with close attention constantly in real time and ensured that the Arduino Uno was storing that data on the SD card. This testing phase gave me the advantage of fine-tuning the software and enhancing response to environmental changes, basically tying in how the solar tracker interpreted sunlight direction and recorded performance data. After minor wire loosening and value mishaps were sorted, we confirm that everything is working. Here is The breadboard Test after the simulation from proteus as showing in the figure 31.

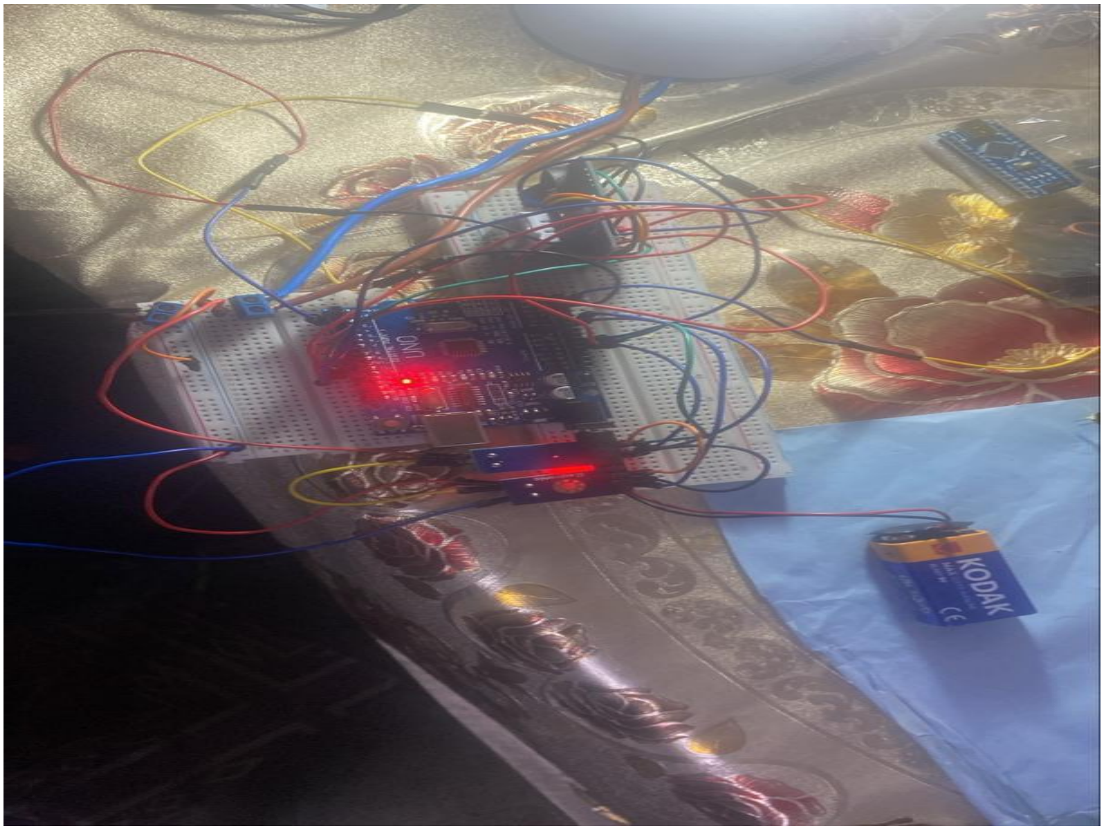


Figure 31: The breadboard Test after the simulation from proteus

2.4.5.4 Component Assembly and Soldering

After testing on the breadboard, we carefully soldered all the components onto the PCB (Printed Circuit Board). We made sure every wire and connection was correct. Then, we tested the board to see if everything worked and if the Arduino could still save the data from the sensors. The image below shows the soldered components on the PCB.

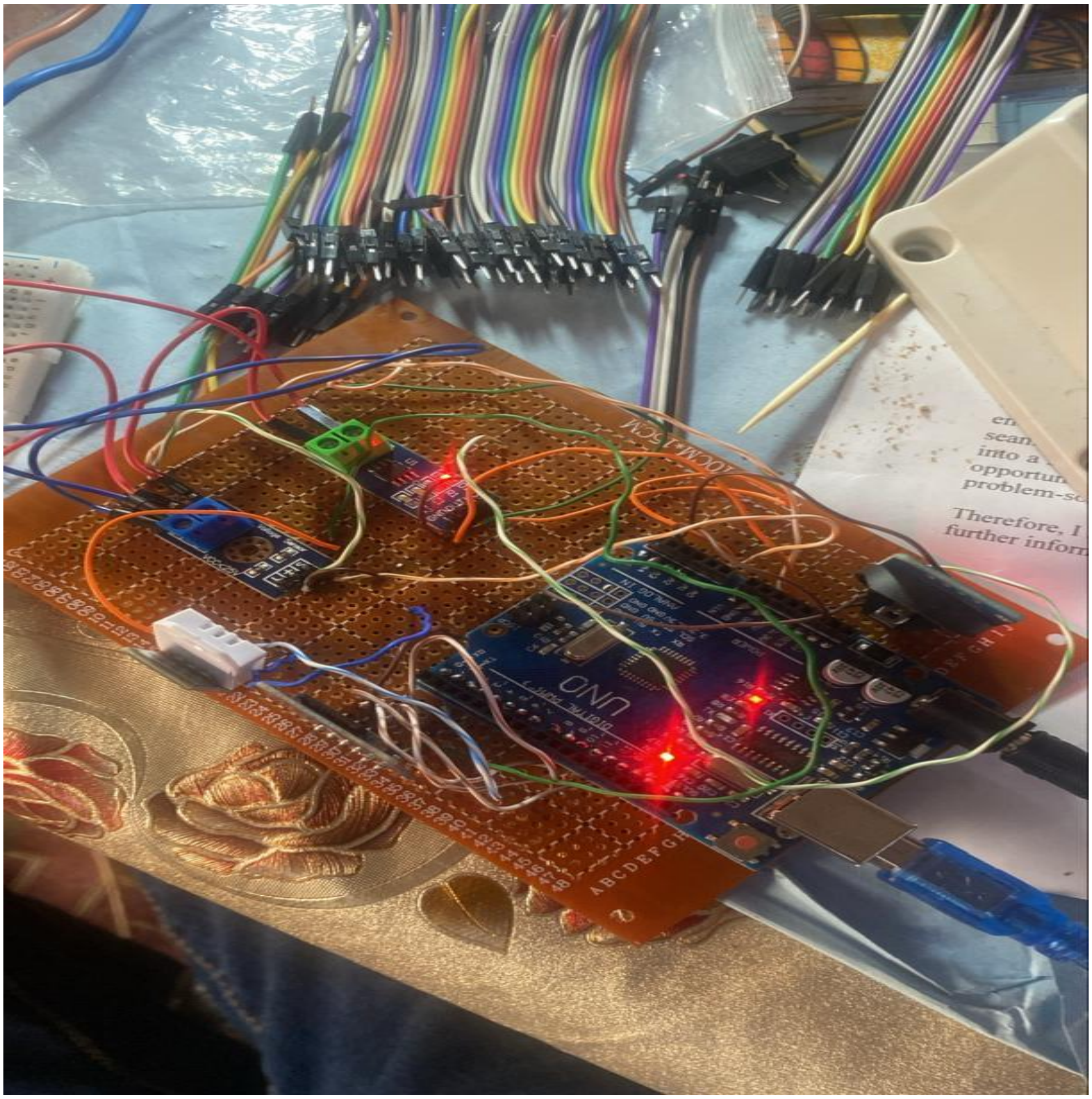


Figure 32: The data Logger final circuit

The Arduino Nano is programmed to record data every minute. It measures voltage, current, temperature, and humidity, adds timestamps using the RTC module, and saves everything in CSV format on an SD card. At the same time, it displays live readings on the serial monitor for real-time observation. The data Logger final circuit is as showing in the figure 32.

Conclusion

This chapter has provided a comprehensive overview of the materials, tools, and methods applied to develop and test a configurable solar tracking system designed for the climate and infrastructure of Ouagadougou. From site selection and system design to data acquisition and cleaning, every step was meticulously planned to ensure accuracy, repeatability, and fairness in performance evaluation. By leveraging affordable, locally available components and open-source platforms such as Arduino and MATLAB, the study ensures accessibility and replicability for future solar projects in similar contexts. The experimental setup allowed for direct comparison between fixed and tracking systems under identical conditions, enabling robust analysis of energy output and system efficiency. The insights gained from this methodology form the basis for the results and discussion in the following chapter, and offer valuable contributions toward the broader goal of enhancing solar energy deployment in high-potential but challenging environments like the Sahel.

CHAPTER3 : RESULTS AND DISCUSSION

Introduction

This chapter presents the results obtained from the experiments carried out during the implementation of the configurable solar tracking system. After outlining the data collection methodology in the previous chapter, we now proceed with a comparative analysis of the performance between a fixed photovoltaic panel and a panel equipped with a single-axis solar tracker. The key indicators studied include voltage, current, instantaneous power, and daily energy production.

The results are examined in relation to the solar irradiance and environmental conditions of the experimental site located in Ouagadougou. This chapter highlights the impact of solar tracking on the energy efficiency of the photovoltaic system and discusses its benefits, limitations, and prospects for improvement. The analysis is based both on measured empirical data and on numerical simulations performed using MATLAB/Simulink tools, in order to validate the experimental observations.

3.1 **Results**

3.1.1 Development and Test of the Configurable Solar Tracker

3.1.1.1 Development

3.1.1.1.1 The result of the PCB (Kicad)

After completing the circuit diagram, we opened the PCB Editor in KiCad and clicked "Switch to PCB Editor" to load all the components from my schematic file. We placed the Arduino Nano, LDRs, 7805 voltage regulator, relays, transistors, and other components carefully on the board, making sure to space the heat-sensitive parts like the regulator and relays. Then, we used the "Route Tracks" tool to draw copper lines between the parts, allowing electricity to flow properly. Once everything was connected, we saved the layout, and KiCad created a file named project11.kicad_pcb. The screenshot below shows how my PCB layout looked in KiCad. Here is the result of PCB layout of the solar tracker project in KiCad as showing in the figure 33.

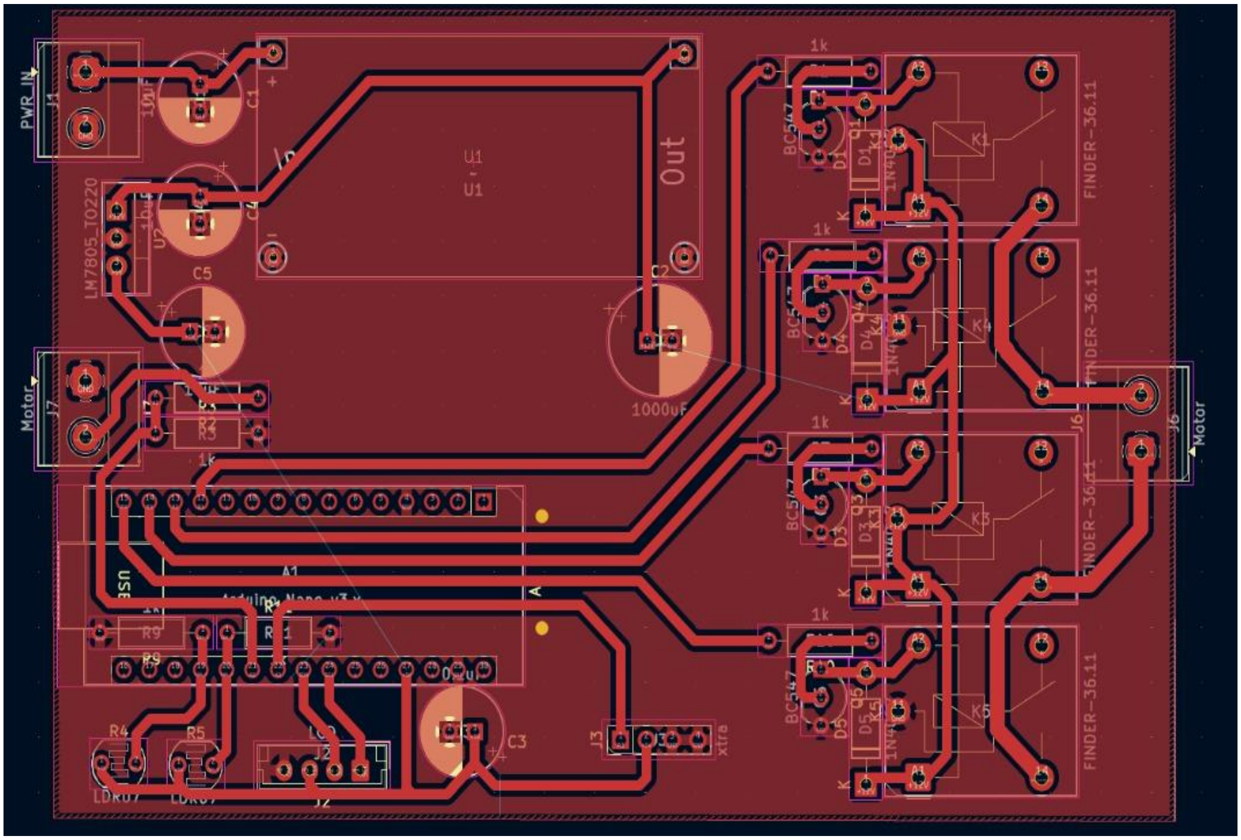


Figure 33: PCB layout of the solar tracker project in KiCad

3.1.1.1.2 Viewing the 3D Model (KiCad)

After we finished designing the PCB, I clicked the **3D View** button in KiCad to see how my board would look in real life. We saw all the parts like the Arduino Nano, LCD, relays, and copper tracks. This view helped me check that everything was in the right place and ready for printing. Here is the result of 3D view of the solar tracker PCB design in KiCad as showing in the figure 34.

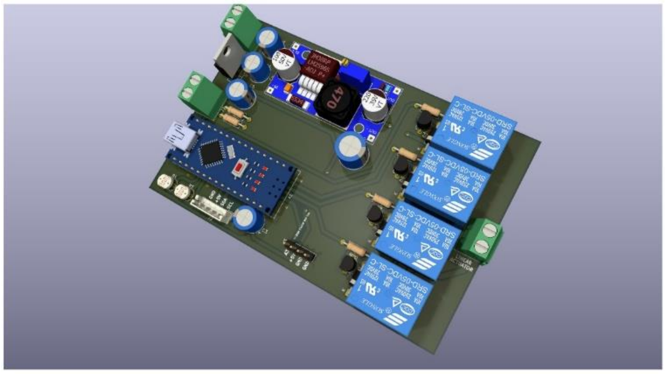
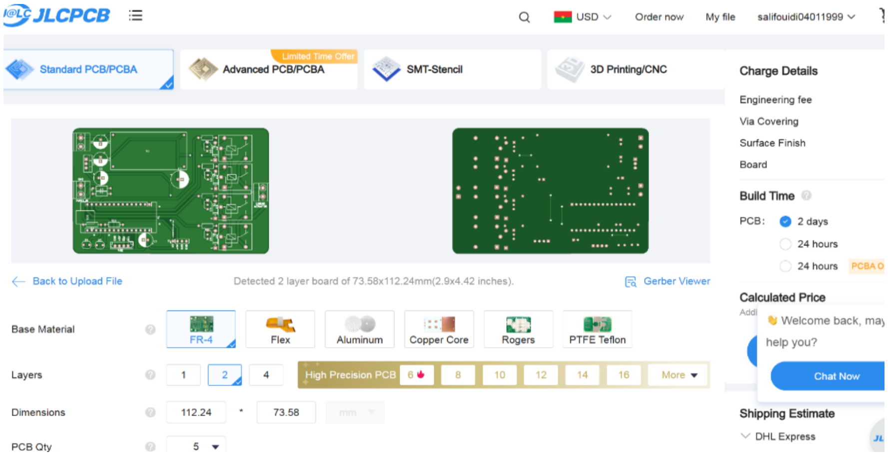


Figure 34: 3D view of the solar tracker PCB design in KiCad

3.1.1.1.3 Uploading Gerber Files and Ordering the PCB

After verifying the 3D layout in KiCad, we generated the Gerber files, which are needed to manufacture the PCB. These files include all the information about the copper tracks, holes, pads, and board outline. We then visited the JLCPCB website and uploaded the Gerber ZIP file by clicking "Upload Gerber File." Once uploaded, the platform displayed a preview of our board layout. We selected the necessary parameters: 2-layer board, FR4 base material, standard thickness (1.6mm), and green solder mask. We also chose the build time (24 hours) and selected the shipping method. The screenshot below shows how the PCB appeared on JLCPCB's interface before confirming the order. This step completed the process, and our PCB was ready for fabrication. The Final PCB Order Setup on JLCPCB is as following in the figure 35.



Detected 2 layer board of 73.58x112.24mm(2.9x4.42 inches).

Base Material: FR-4

Layers: 2

Dimensions: 112.24 * 73.58 mm

PCB Qty: 5

Build Time – PCB: ● 2 days ○ 24 hours ○ 24 hours

Figure 35 : Final PCB Order Setup on JLCPCB

3.1.1.1.4 PCB Assembly and Shadow Response Test

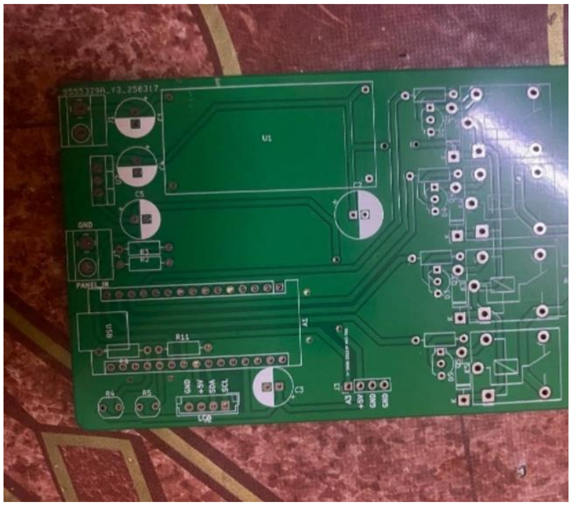


Figure 36 : Final Manufactured PCB

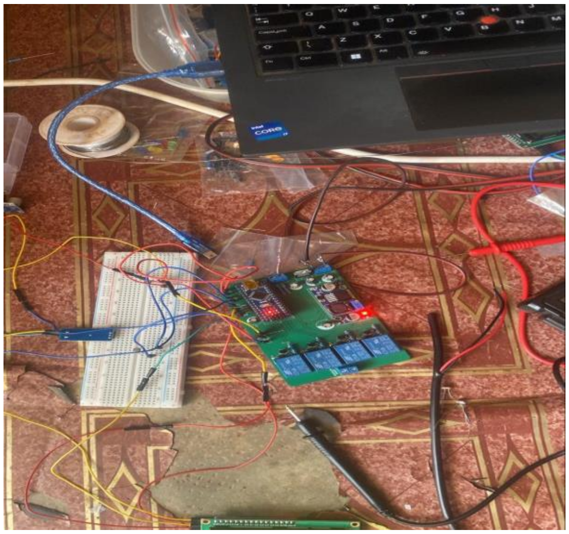


Figure 37: Soldered Components for Solar Tracking System

- The figure 36 shows the printed circuit board (PCB) manufactured via JLCPCB, based on the schematic and layout created in KiCad. The electronic components such as the Arduino Nano, 7805 voltage regulator, relays, transistors and connectors were carefully arranged and routed to ensure optimal performance of the solar tracking system. The board was printed carefully attention to leave the space of each component and positioning designed to minimize interference and heat buildup, especially around components like the voltage regulator and relays.

- The figure 37 displays the fully assembled PCB after soldering all the main electronic components. Once the components were soldered in place, external devices such as the linear actuators were connected to the output terminals. A practical shadow test was then performed to evaluate the responsiveness of the tracking system. First, one of the Light Dependent Resistors (LDRs) was manually shaded by hand and later the phone flashlight was used to simulate light variations. The system reacted as expected: the corresponding relay was activated and the actuator moved to adjust the panel direction. This confirmed that the tracking system correctly detects changes in light intensity and responds in real-time, as designed.

3.1.1.1.5 System Architecture and Operation of the Solar Tracker

The developed configurable solar tracking system consists of an Arduino Nano microcontroller, four Light Dependent Resistors (LDR1 to LDR4), two linear actuators, four 12V relays (RL1 to RL4), four BC547 transistors (Q1 to Q4), four 1N4007 diodes (D1 to D4), a 12V rechargeable battery (BAT1), a red indicator LED (D5), and an LM016L LCD display connected via a PCF8574 I/O expander (U1). The system also integrates various resistors (1kΩ, 5kΩ, 10kΩ, 47kΩ, and 330Ω) and capacitors (100µF and 1000µF), as well as a 7805 voltage regulator (U2) for power regulation. All components were mounted and tested on a breadboard during the early phase of implementation. Indeed, the configurable solar tracking system was developed to execute a lot of tasks such as:

- ❖ Tracking the position of the sun using light sensors. Thus, the four Light Dependent Resistors (LDRs) are used to detect sunlight from different directions. But, before even their insertion in the system, the LDRs were first tested by implementing an Arduino code which was also uploaded to the Arduino Nano microcontroller. The obtained results confirmed that the LDRs could accurately detect changes in light intensity, thus making them suitable for the purpose of the tracking system.
- ❖ Automatically adjusting the solar panel orientation. The Arduino Nano receives light intensities from the four LDRs and makes decisions about the movement of the actuators. The system energizes the appropriate relay to drive one of the two linear actuators according to the direction of the strongest sunlight. This real-time adjustment allows the panel to be continuously aligned with the optimal direction for solar exposure.
- ❖ An autonomous system up and running by itself. It runs on a 12V battery, which is source to power the system. The voltage regulator model 7805 is utilized to provide 5V to components,

such as the Arduino Nano and the LCD. It, therefore, does not require any external power supply for the configurable solar tracking system.

- Local feedback and control display shall be established. It displays the current and voltage values in real-time on an LM016L LCD with I2C interface. This display allows the user to monitor the system's electrical performance and provides essential information for system observation and maintenance.

Finally, industrially, the configurable solar tracking system is very easy to use because it autonomously performs all its operations without human intervention. Indeed, whenever the light intensity is changed, the system calculates the changes and moves accordingly to change the panel position in response, ensuring that it tracks the sun most effectively at all times.

3.1.1.2 Testing

The configurable solar tracking system was tested during one (1) day but not in a laboratory. The whole test protocol was executed in open air under natural sun light on the 11th of June 2025. The main mode of verification of the solar tracker's behavior was observing its daily course by taking pictures at three (3) different times in the day: around 9:30, 12:55, and 16:00. These visuals clearly showcase the solar panel orientation was changed. That means the solar tracker precisely followed the sun's path throughout the day. The obtained pictures will be used to support and justify the correct operation of the solar tracking system. They show that the actuators responded correctly to the light variation detected by the LDRs and aligned the panel well from east to west as expected.

Tracker Position at 16:00 Tracker Position at 12:55 Tracker Position at 9:30

Figure 38 : Solar Tracker Positioning Throughout the Day

As shown in the figure 38, the tracker's physical response to sunlight is confirmed throughout the day. The panel faced east and captured the low-angle morning sunlight at 9:30. The panel had shifted to a horizontal position where it directly faced the sun at its highest point in the sky around 12:55. Therefore, the panel moved to the west at 16:00 to follow the sun going down. This shows that the system could keep moving to stay in a good position with the sun, which helps get more solar energy.

3.1.2 Development and Test of Data Loggers

3.1.2.1 Development

The developed solar data loggers are composed of an Arduino Uno microcontroller, a 9V battery, a 7805 voltage regulator, an ACS712 current sensor, a DCVS30-H16S8 voltage sensor, a DHT11 temperature and humidity sensor, a Real-Time Clock (RTC) module (DS1307 or DS3231), and an SD card module for data storage. The system also includes necessary pull-up resistors, a 1kΩ resistor for the DHT11, and electrolytic capacitors for voltage smoothing. All components were mounted and tested on a breadboard during the early phase of implementation. In fact, the solar data logger was made to accomplish many tasks such as:

- Measuring the current output from the solar panel. The ACS712 sensor is used to detect the electric current flowing from the panel. It is connected to analog pin A0 of the Arduino Nano. The sensor was first tested with a simple Arduino code to confirm its ability to measure current variations accurately, making it suitable for integration into the logger.
- Measuring the voltage from the solar panel. The DCVS30-H16S8 voltage sensor was employed to convert voltage levels to analog signals. Its output is linked to analog pin A1 of the Arduino Nano. Before implementation, it was tested and showed that it produced readings consistent with a standard multimeter, confirming its accuracy and suitability.
- Monitoring environmental conditions. The DHT11 sensor is connected to digital pin D2, is responsible for capturing ambient temperature and humidity. Before integration, it was tested with Arduino to ensure reliable data output. It was selected for its affordability and simplicity in implementation.
- Generating real-time timestamps. The RTC module provides date and time information even when the system is powered off. It is connected via I2C (SDA to A4 and SCL to A5).

The module was pre-configured and tested with the Arduino Nano to verify the integrity of date-time values.

- Storing the collected data. The SD card module is used to store the following variables such as current, voltage, temperature, humidity, and time data. The SD card module is connected to the SPI interface (CS to pin 10, MOSI to pin 11, MISO to pin 12, and SCK to pin 13). During test, the module has successfully created and opened data files, confirming that data logging worked properly.

3.1.2.1.1 Installation of the Complete System on the Site

After the development and individual testing of both the configurable solar tracking system and the solar data logger, the complete system was installed outdoors for real-world evaluation. The tracker was mounted on a stable metal structure to ensure proper support and exposure to sunlight throughout the day. The electronic components, including the Arduino Nano, relays, sensors, and battery, were carefully enclosed in a protective 3D-printed box to prevent damage from dust, moisture, and heat. The data logger components were positioned close to the panel for accurate measurement of electrical outputs and environmental conditions. The linear actuators were connected to the mechanical structure and powered by the 12V battery, allowing smooth adjustment of the panel's orientation. The wires were organized carefully to prevent tangling and ensure the system was safe to use. Once the system was fully installed, it was powered on and closely monitored to verify correct operation. During the initial live test, the tracker successfully followed the sun’s path, while the data logger continuously recorded values such as current, voltage, temperature, humidity, and timestamps. This practical installation confirmed that the system was ready for field testing under natural sunlight conditions. The images below show the complete setup: the figure 39 and 40 present the data logger and the solar tracker control system, while the figure 41 shows the entire solar tracking system fully installed and operational on site.

Figure 39 : Data Logger and Solar Tracker Control Setup

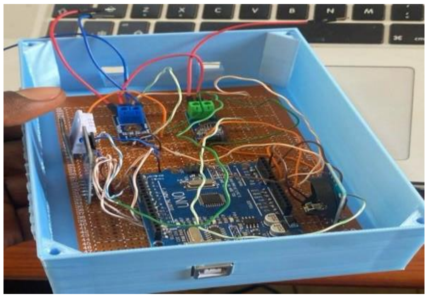
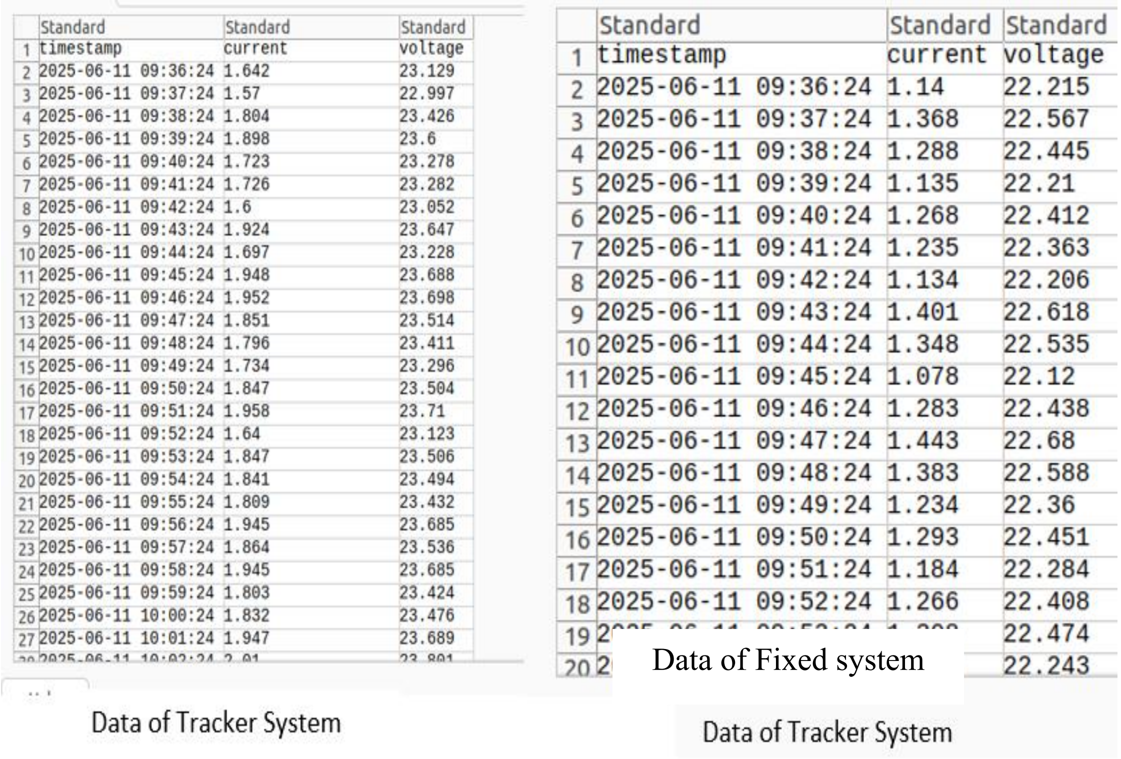


Figure 40 : Data Logger

Figure 41 : Solar Tracker

3.1.2.1.2 Testing

The solar data logger system was tested during one (1) day but not in a laboratory. The test was conducted in open air on the 13th of April 2025 using a 9V battery as the power source instead of a solar panel. The goal was to verify the proper functioning of the components and data collection process. During the test, the data logger was connected to a small battery which powered bulb as a visual indicator of current flow. The bulb turned on when the current was detected. It confirmed that the circuit was closed and functional. The Arduino Uno successfully collected data from all connected sensors, including current, voltage, temperature, and humidity. These data were timestamped using the RTC module and saved to the SD card module in real-time. After testing, the SD card was removed and read on a computer. The stored data were well formatted, showing the expected values with correct timing. This confirmed that the data logger was able to measure, process, and save information accurately using only a battery supply. Thus, this preliminary test validated the system's readiness for solar integration in future experiments. The figure 42 below presents the real-time current and voltage measurements recorded by the solar data logger system during field testing, illustrating its successful functionality in monitoring and saving electrical parameters.



	Standard	Standard	Standard
1	timestamp	current	voltage
2	2025-06-11 09:36:24	1.642	23.129
3	2025-06-11 09:37:24	1.57	22.997
4	2025-06-11 09:38:24	1.804	23.426
5	2025-06-11 09:39:24	1.898	23.6
6	2025-06-11 09:40:24	1.723	23.278
7	2025-06-11 09:41:24	1.726	23.282
8	2025-06-11 09:42:24	1.6	23.052
9	2025-06-11 09:43:24	1.924	23.647
10	2025-06-11 09:44:24	1.697	23.228
11	2025-06-11 09:45:24	1.948	23.688
12	2025-06-11 09:46:24	1.952	23.698
13	2025-06-11 09:47:24	1.851	23.514
14	2025-06-11 09:48:24	1.796	23.411
15	2025-06-11 09:49:24	1.734	23.296
16	2025-06-11 09:50:24	1.847	23.504
17	2025-06-11 09:51:24	1.958	23.71
18	2025-06-11 09:52:24	1.64	23.123
19	2025-06-11 09:53:24	1.847	23.506
20	2025-06-11 09:54:24	1.841	23.494
21	2025-06-11 09:55:24	1.809	23.432
22	2025-06-11 09:56:24	1.945	23.685
23	2025-06-11 09:57:24	1.864	23.536
24	2025-06-11 09:58:24	1.945	23.685
25	2025-06-11 09:59:24	1.803	23.424
26	2025-06-11 10:00:24	1.832	23.476
27	2025-06-11 10:01:24	1.947	23.689
28	2025-06-11 10:02:24	2.01	23.801

Data of Tracker System

	Standard	Standard	Standard
1	timestamp	current	voltage
2	2025-06-11 09:36:24	1.14	22.215
3	2025-06-11 09:37:24	1.368	22.567
4	2025-06-11 09:38:24	1.288	22.445
5	2025-06-11 09:39:24	1.135	22.21
6	2025-06-11 09:40:24	1.268	22.412
7	2025-06-11 09:41:24	1.235	22.363
8	2025-06-11 09:42:24	1.134	22.206
9	2025-06-11 09:43:24	1.401	22.618
10	2025-06-11 09:44:24	1.348	22.535
11	2025-06-11 09:45:24	1.078	22.12
12	2025-06-11 09:46:24	1.283	22.438
13	2025-06-11 09:47:24	1.443	22.68
14	2025-06-11 09:48:24	1.383	22.588
15	2025-06-11 09:49:24	1.234	22.36
16	2025-06-11 09:50:24	1.293	22.451
17	2025-06-11 09:51:24	1.184	22.284
18	2025-06-11 09:52:24	1.266	22.408
19	2025-06-11 09:53:24	[illegible]	22.474
20	2[illegible]	[illegible]	22.243

Data of Fixed system

Data of Tracker System

Figure 42 : Screenshots of Data Collected by the Solar Data Loggers

3.1.3 Electrical Performance Comparison: Dual-axis Tracker Vs Fixed Panel

3.1.3.1 Current

It has been discovered that the proposed dual-axis tracking system is a more effective method for generating electric current than the traditional fixed solar panel system. The average current output of the fixed system was measured at approximately 1.68 amperes, while the dual-axis tracker achieved an average of 2.14 amperes. The highest value recorded by the tracker reached around 2.37 A which greater than 2.1 A for the fixed system as showing in figure 43.

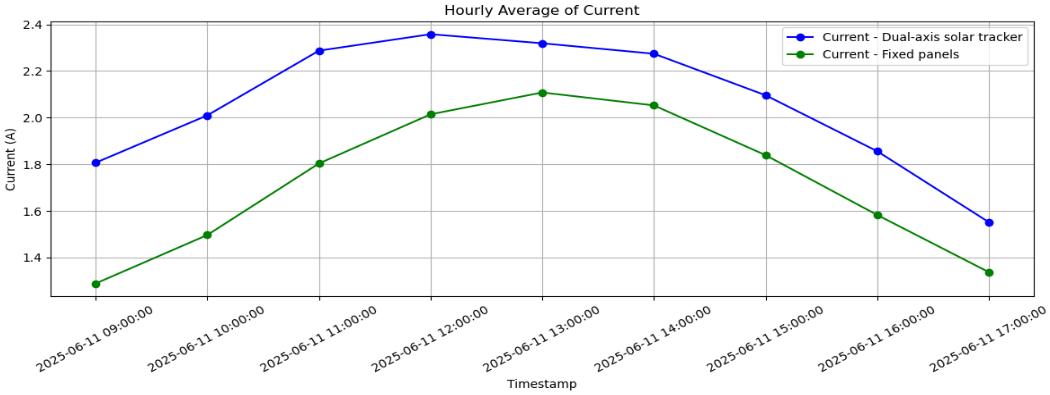


Figure 43 : Hourly Current Output: Dual-Axis Tracker vs Fixed System (June 11, 2025)

3.1.3.2 Voltage

The figure 44 has been determined that the implemented dual-axis solar tracking mechanism is a more efficient approach for producing electrical voltage than the conventional fixed-panel setup. The mean voltage output of the fixed system was roughly 23.60 volts while the dual-axis tracker got a higher average of about 24.05 volts. The maximum voltage recorded by the tracker was approximately 24.35 V at midday which is clearly higher than the top value of nearly 23.65 V measured from the fixed configuration. the overall difference in voltage output is moderate and follows a similar trend like current.

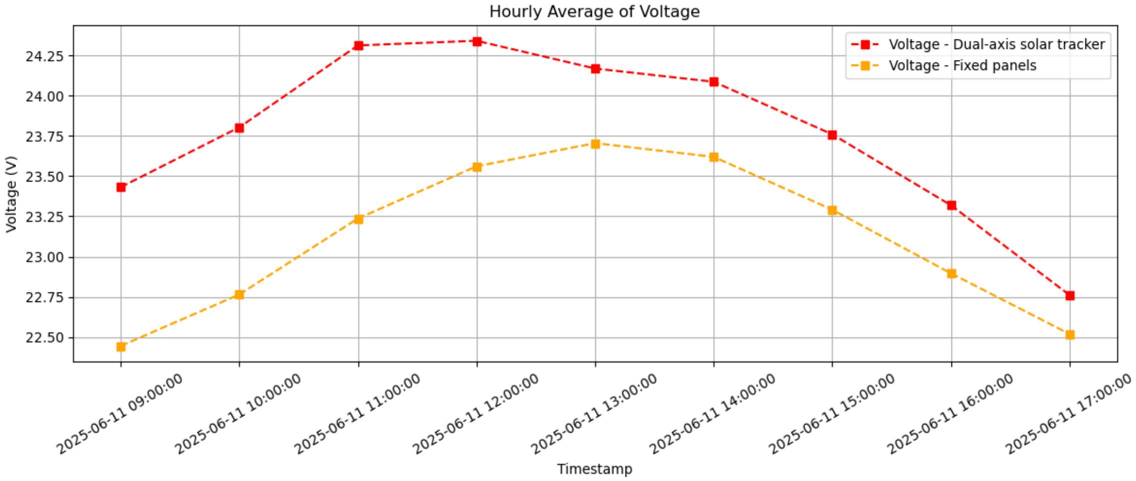


Figure 44 : Hourly Current Output: Dual-Axis Tracker Vs Fixed System (June 11, 2025)

3.1.3.3 Power

Power output showed a more noticeable difference. From 09:00 to 16:00, the dual-axis tracker worked well the whole time while the fixed panel did less. The tracker gave a maximum power of about 57 W whereas the fixed panel gave about 50 W. Both power curves go up in the morning, reach their highest point around 13:00–14:00, and go down after that. However, the tracker always gave more power during the sunny hours as showing in figure 45.

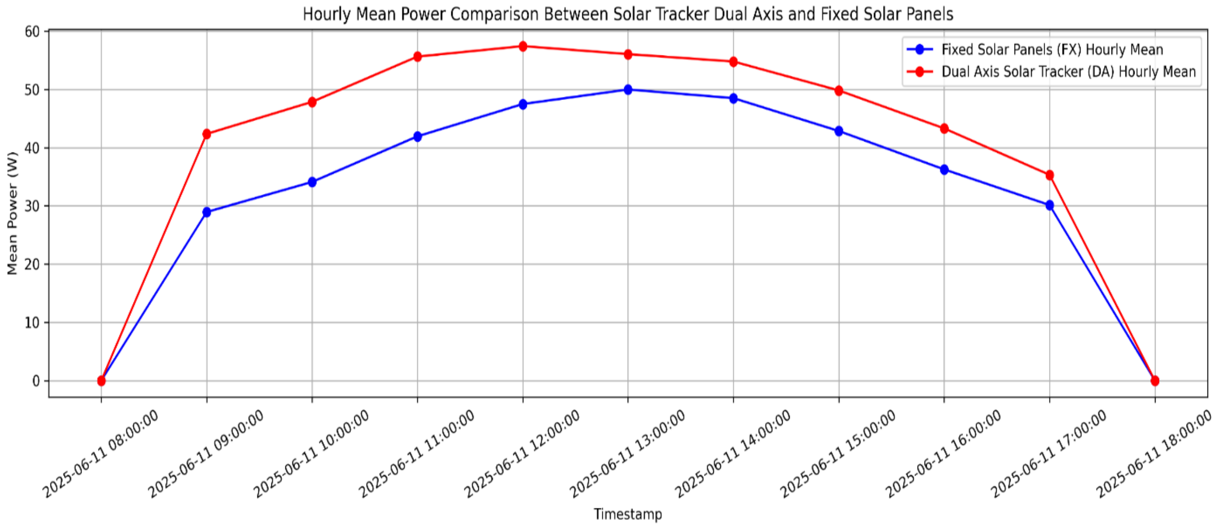


Figure 45 : Comparative Analysis of Hourly Power Output: Dual-Axis Tracker Vs Fixed Panels

3.1.3.4 Energy

The figure 46 showed how much energy two types of solar systems made on June 11, 2025.

The dual-axis solar tracker produced around 403.7 watt-hours (Wh) of energy during the day,

while the fixed solar panels made about 331.3 Wh on the same day.

It produced about 72.4 Wh more which is an exact gain of 21.85% compared to the fixed panel Both systems used the same daylight hours but the dual-axis tracker can follow the sun’s movement during the day. This helped it collect more sunlight and produced more electricity.

This means the dual-axis tracker is more efficient and gives better performance for solar energy production. It shows that following the sun helps increase the energy output.

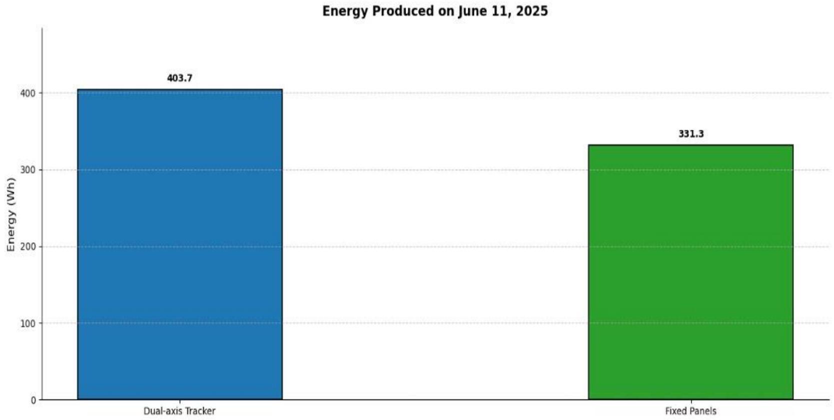


Figure 46 : Energy Comparison: Dual-Axis Tracker Vs Fixed Panels

3.2 Discussion

In their study titled "Performance Analysis of a Dual-Axis Solar Tracking System in Arid Regions" in 2023, Bouchama et al. made a dual-axis solar tracker in the Algerian desert and found that it produced more energy than a fixed solar panel. Their results showed that the use of dual-axis tracker gave better energy in places where the sunlight is abundant like arid regions. Their study also showed that the tracker worked well under real weather conditions, including high temperatures and changing sun angles during the day. Also, Gakou et al. (2021) did a study in Mali about solar trackers. They looked at the cost and the energy produced by the solar tracker system. They found that even if the dual-axis system costs more in the beginning, it gives more energy over time, which makes it a good choice. They said that it is important to make the system fit the weather and needs of the local area. They also said that using local materials helps reduce the cost and makes maintenance easier. To our knowledge, no other study has tested a dual-axis solar tracker with local components and a data logger in Burkina Faso before. Ouagadougou receives a lot of sunlight. However, most of solar panels there are fixed and cannot follow the sun’s movement. This leads to lower energy production particularly during the early morning and late afternoon when the sun is at a low angle. Therefore, there is a need to try new systems that can help improve energy production. In this work, we made and tested a dual-axis solar tracker with a data logger. We used simple and low-cost electronic components to make the system. We tested it on June 11, 2025. The results showed that the tracker gave better results in current, voltage, power, and energy than the fixed system. For example, the tracker made 403.7 Wh of energy, while the fixed one made 331.3 Wh. The current was also higher during most of the day with the tracker system. The voltage and power values followed the same pattern, always showing better performance with the tracking system. Therefore, this supports our research idea that a solar tracker made for the local area produces more energy than a fixed panel. The system follows the sun and helps the panels get more light, which gives better energy results. It also helps to reduce energy losses and gives more stable energy during the day. However, we also noticed that the system needs regular checking and cleaning to keep working well, especially because of dust. We also believe that the solar tracker system can be used in other cities of the Sahel region. The solar tracker can help to better use solar energy and improve energy access for local people in Burkina Faso and nearby countries. The dual-axis solar tracker can help produce more electricity for rural electrification projects, schools, health centers and homes where access of electricity is still limited or not available. Consequently, the use of solar trackers like the one we made could be a simple but strong way to help solve the energy problem in these areas.

CONCLUSION AND PERSPECTIVES

This research can be considered as a first step for the development of solar trackers with their data loggers in West Africa. It focused on the optimization of photovoltaic energy production through the design and testing of a configurable solar tracking system in Ouagadougou, Burkina Faso. The proposed system was built with simple and low-cost components available locally. A data logger was integrated into the system to measure electrical values such as current, voltage, power, and energy.

Therefore, this work confirms that the developed solar tracking system efficiently contributes to a better energy production compared to a fixed system, based on some assumptions made. Indeed, the main findings of this research are:

- ❖ The dual-axis solar tracker generated more energy output than the fixed solar panel. The dual-axis tracker Produced 403.7 Wh of energy but the fixed panel produced 331.3 Wh, On June 11, 2025.
- ❖ The Configurable Solar Tracker is developed using known technologies and adjusted to fit the real weather and living conditions of Ouagadougou and the Sahel region.
- ❖ The integration of a data logger allowed the measurement and recording of the performance of the system in real-time.

The verification of the hypotheses of this research is as follows:

- ✓ The dual-axis tracker gave better results in energy production compared to the fixed panel under the same environmental conditions in Ouagadougou.
- ✓ The use of existing technologies adapted to the Sahelian context made it possible to design a working tracking system.
- ✓ The data logger contributed to better monitoring and performance evaluation of the PV system.

The Configurable Solar Tracker that is developed in this work, is not yet a well-used product ready to be used for a long period. The current study was carried out over only one day. For this raison, it is necessary to test the system for a longer period to confirm its stability and performance under different weather conditions.

So, the system needs:

- ❖ A Printed Circuit Board (PCB) for the solar tracker has already been made to reinforce the electronic connections and improve durability.
- ❖ A PCB for the data logger still needs to be developed to ensure full robustness of the entire system.
- ❖ A 3D printed enclosure to protect the components and allow the system to be installed outdoors.
- ❖ A local database or cloud system can be used in order to store the data securely and allow future analysis.

Also, because the system is configurable, it will be important to test the single-axis mode separately and compare it with the dual-axis mode. This will help determine the best option depending on cost and energy production.

In addition, it is recommended to include solar irradiation as one of the variables that the data loggers record. This will help understand the relation between sunlight and energy produced.

Finally, this system can be deployed and tested in other locations of Burkina Faso and the Sahel. It can be used for rural electrification projects, schools, health centers and households where access to electricity is still limited. Consequently, this kind of solar tracking system could be an important tool to contribute to solving the energy problem in these areas.

Conclusion

L’analyse des résultats expérimentaux a clairement démontré l’intérêt de l’utilisation d’un suiveur solaire configurable dans le contexte sahélien. Comparé au système fixe, le panneau mobile a enregistré une production énergétique supérieure, traduisant une meilleure captation du rayonnement solaire tout au long de la journée. La corrélation entre l’orientation dynamique du panneau et la position apparente du soleil a permis d’optimiser l’angle d’incidence, réduisant ainsi les pertes énergétiques.

Les données collectées et les simulations confirment la pertinence de la solution proposée, notamment dans les zones à fort ensoleillement comme Ouagadougou. Toutefois, certaines limitations, telles que la dépendance au vent, les contraintes mécaniques et la consommation énergétique du moteur, méritent d’être prises en compte pour améliorer le système. Ces résultats ouvrent la voie à des perspectives de recherche orientées vers l’optimisation énergétique globale du dispositif, en intégrant notamment l’intelligence artificielle pour une orientation plus intelligente et autonome.

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